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A Laboratory study of ink splitting forces at different film thicknesses and an investigation of the stefan equation

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A Laboratory Study of Ink Splitting Forces at Different Film Thicknesses and An Investigation of The Stefan Equation

By

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the School of Printing Management and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

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ABSTRACT

Ink tack is a term used by printers to describe the force required to split an ink film. Such film splitting is influenced by rheological and adhesive properties as well as the internal cohesion of ink. Furthermore, the concept of ink tack in printing is associated with the forces or energy developed in the splitting of ink film at the exit of a printing nip.

Stefan studied the forces required to split a thin film. He found that the force required to split a thin film is inversely proportional to the cube of the thickness of that film. This association between the film thickness and film splitting force has been questioned in the literature and by this study.

In printing, the practical condition related to ink film splitting forces might be revealed by measurement on the Inkometer (Inkometer response), paper picking, and ink trapping. This study used these responses.

The purpose of this study was to investigate the relationship (not mathematical) between ink film thickness (0.6 to 5.4 μm) that should include the film thicknesses found on presses.

Experiment one was accomplished on the Inkometer with the two black vegetable-oil-based inks to obtain the Inkometer response under the proposed three way factorial experimental design (inks, ink film thicknesses, and time.) Experiment two made use of the IGT Printability Tester with the same inks, the IGT oil, and one of the paper samples to find the critical picking velocity under the proposed two way

factorial experimental design (fluids, ink film thicknesses.) Experiment three was accomplished with the IGT Printability Tester, the same inks, and two substrates including a second paper sample and a plastic film. The response is gravimetric trapping under the proposed three way factorial experimental design (inks, substrates, and ink film thicknesses.) Inkometer response, picking velocity, and gravimetric trapping are not direct measurements of film splitting force. They are related to film splitting force. The greater the Inkometer response, the more tacky the ink. The higher the picking velocity the lower the splitting force. With increased gravimetric trapping of the second-down inks, the more tacky the first-down inks.

The data was analyzed by ANOVA at a level of significance equal to 0.05 (two-sided) to test the null hypotheses. The null hypotheses are the following:

H_{01}: There is no significant effect due to vegetable-oil-based ink film thickness on ink tack as measured by an Inkometer.

H_{02}: There is no significant effect due to film thickness of vegetable-oil-based fluid on picking velocity under the proposed experimental design on the IGT Printability Tester.

H_{03}: There is no significant effect due to the first down vegetable-oil-based ink film thickness on ink trapping capability under the proposed experimental design on the IGT Printability Tester.

An overview of the results show that the ink film thickness could affect the Inkometer response and gravimetric trapping, and the oil-based fluids' film thicknesses could affect the picking velocity within the film thicknesses range of 0.6 to 5.4 μm. The graph of data, regression analysis, and R^2 are prepared for predicting and evaluating the specific tendency of the measurements (Inkometer response, picking velocity, and gravimetric trapping) when ink film thicknesses change. They also show the tendency of change of the splitting forces at the different film thicknesses.

The other general results on the basis of the graphs, regression analysis, and R^2 show that the Inkometer response increases when ink film thicknesses increased from 0.6 to 5.4 μm with both of the inks and at each time interval. Picking velocity decreased when the ink film thicknesses increased up to about 3.0 μm and then increases with increased ink film thickness from around 3.0 μm to 5.4 μm at each the ink level. The gravimetric trapping on both the paper and plastic substrates and with both inks decrease with the ink film thickness increased from 0.6 to 5.4 μm. There is no consistent agreement with the equation proposed by Stefan.

CHAPTER 1

INTRODUCTION

In printing, ink must meet a remarkable number of requirements. On press, the ink fountain is both a reservoir and metering mechanism to feed the ink into the press rollers. The ink train there after distributes, transfers, causes structural breakdown, and covers the printing plate adequately without filling in any of fine halftones while maintaining an appropriate solid ink density. Then the image that is the ink must transfer to paper without serious distortion. Lastly, it must set and dry on the substrate sufficiently fast with no set-off to press parts or paper. All this must be done while the web of paper is moving through the press at speeds presently approaching 2000 fpm. In a fraction of a second the ink is made to flow, split, and stick when it meets the paper. It is transferred and set-dryed in a fraction of a second.

Lithographic inks have certain properties or characteristics that govern performance on press such as flow, internal cohesiveness, stickiness, and ease with which roller action can reduce an ink to a workable consistency. The properties found most important to performance are viscosity, length, thixotropy and tack.[1]

Ink tack

Tack is not a well-defined ink property. It is related to ink viscosity for ink manufactured from the same chemical components,[2] and, as proposed by Strong,[3] how " easily " a blanket releases ink. In the context of paper surface deterioration in the printing nip, tack is defined by the maximum force exerted on the paper surface by the ink, from the onset of cavitation in the ink film to the rupture of the ink filament. This proposed definition of tack is an extension of the definition for the printing implied by Kehla *et al.*[2] in the parallel plate tack measuring method. Normal definition of tack follows.

Tack[4] is a concept that is widely used to describe the forces or energy involved in the separation of two surfaces joined by a thin liquid film (Voet, 1976). Tack[5] is a measure of the forces required to split a film of ink. Such film splitting is influenced by rheological and adhesive properties, in addition to the internal cohesion of the ink. Furthermore, the concept of ink tack[6] in printing is primarily connected with the force or energy developed in the splitting of ink films at the exit of a printing nip.

As a measure of the forces involved in ink film splitting, tack is relevant to all stages where distribution or transfer takes place. Too high a tack can cause some form of rupture in the substrate (picking and linting) where the tack is only marginally too high for the strength of the substrate a small degree of coating pick or fiber linting will occur at each impression. From the point of view of minimizing the risk of substrate disruption, particularly with weak, low-quality papers, it is clearly advantageous to use inks with as low a tack as possible. Also, in multi-color printing, both the initial tack and changes in tack during the fraction a second between the application of successive ink colors to the paper surface are important to ink setting and to " trap", or the ability of a wet ink film to accept another ink film on top of itself. Too low a tack can produce a variety of problems within the ink roller train right through to final print quality[7] (dot gain, trapping, and roller slippage, inadequate ink feed, and distribution). Descending tack sequence is often used during the multi-color printing to prevent poor trapping or back trapping.

The ink tack in the quality control of the materials is monitored by the measurements at different time on the Inkometer. The interesting thing is the degree of the association between the tack measurements on the Inkometer and the actual critical picking velocity and trapping percentage.

The Stefan equation

In the late 1800's, a scientist named Stefan studied the forces required to split a thin film. He found that as the viscosity of the liquid between two plates was increased, the force required to split that film, or to separate the plates, increased. Also, increasing the velocity of separation of the two plates increased the force, as did increasing the area of the two plates. He also showed that the force required to split a thin film was inversely proportional to the cube of the thickness of the film. These observations can be represented in an equation:

$$F = VSA / t^3 \qquad (1)$$

If applied to printing this equation shows that the force required to split a thin ink film on a press is related not only to the ink body itself, but also to the speed of the press and the area and thickness of the ink. The ink film of greatest interest to the printer is the one between the blanket and the paper, or, in the case of trapping, between the second-down ink and the print or the first-down ink.[8]

As presented above, the " F " in Stefan equation represents force, " V " is the viscosity of the ink, and " S " represents the speed of the press. (One should properly refer to the velocity of the separation, but there is already one " V " in the equation, and printers refer to the speed rather than the velocity of the press). " A " is the area of the film being split, and, as every printer knows, picking is most noticeable in solids where the film covers a large area between the blanket and the paper.

Statement of the problem

The last term in Stefan equation t^3, the cube of the thickness, is hard to understand when the practical printing condition is involved. Some of studies have proposed theories to evaluate forces responsible for fiber removal in printing nips or to directly measure the splitting force in the laboratory. Some of the approaches are in some way related to the Stefan equation and proposed that the Stefan equation does not apply to printing conditions, [2 9-15] or, even, challenged the Stefan equation.[15] On the other hand, this equation is still used[16-20] to justify the decrease in the force applied to the paper surface when ink film thickness is increased. The effect of ink film thickness on tack appears to require study.

Purpose of the study

The major purpose of the study was to find the relationship (not mathematical relationship) between ink film thickness and ink film splitting forces within the thicknesses from 0.6 μm to 5.4 μm which is expected to cover the range on presses.

The study of ink splitting force at different film thickness was proposed with three types of responses using an Inkometer, picking velocity, and gravimetric trapping on the IGT Printability Tester to resolve the question of the effect of ink film thickness on splitting force. The function and relative information of the Inkometer and the IGT Printability Tester will be introduced later.

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CHAPTER 2

THEORETICAL BASIS

Printing nip profile

A mathematical simulation of the flow of ink in the printing nip is difficult since the actual printing process involves a non-Newtonian liquid*, a deformable roller, a deformable paper substrate, and ink penetration into paper (Figure 1).

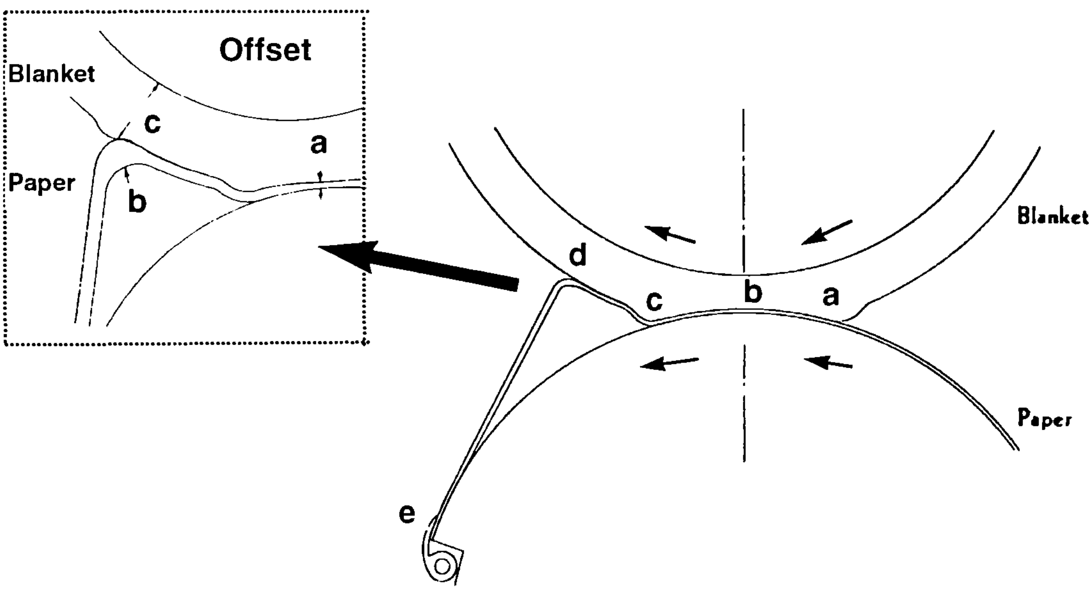

Figure 1[1] Printing nip (sheetfed) shows the configuration of elements in impression

In Figure 1, the blanket conforms to the paper surface, ink wets the paper surface, and some absorption of ink vehicle into the paper takes place. In fact,

* Non-Newtonian fluids do not proportionally change in flow with increasing force.

the contact area continuous from point a as far as d. With regard to picking, this period of time is important since the absorption of ink vehicle can change both the paper surface and the ink film. Similarly, the printing pressure exerted between blanket and paper is important. Enough pressure must be provided to produce complete coverage of the paper by the ink in the printed areas.

After the paper passes point c, it adheres to the blanket as far as d. This distance cd depends on the pull of the ink, stretch of the paper, and slack in the paper introduced by the way the impression cylinder and transfer grippers handle it. The distance from the line of centers of the cylinders b to d, and the cylinder surface velocity, v, determine the velocity of separation, V, of ink and paper perpendicular to the paper surface.[1]

The tack or pull of the ink at the velocity of ink film rupture determines the force that acts on the paper surface and tends to pick it. While this tension is being applied to the paper surface through the ink film, the paper increases in thickness as shown at b in Figure 1.

This paper distortion is important in that it cushions the ink film rupture. The separation velocity V is the rate of separation between the back of the blanket and the side of the paper not being printed. It is composed of the sum of the blanket, ink film, and paper deformation velocity velocities. The more the paper can be deformed without picking, the smaller the ink film deformation velocity and thus the smaller the force required to rupture the ink film.[1] The pick tester simulates those conditions so that the total effect is the same as on the printing press.

Figure 2[2] (Pangalos *et al* ., 1985), shows nip flow between one rigid and one compressible roller is described by a complex flow pattern. As ink enters the nip region, it is subjected to a converging flow, and a positive pressure (compression) builds up. This pressure runs counter to the dominant drag flow. At the nip exit, the two rollers separate. As a consequence, the ink is subjected to the extensional flow in the direction normal to the roller surfaces, and a tensile stress* (or negative pressure) develops within the liquid. Since inks show only a limited capacity to withstand tensile stress, the ink film splits between the two rollers, which results in the transfer of the image from printing plate to paper. The detailed explanation is shown in the section on the film splitting mechanism.

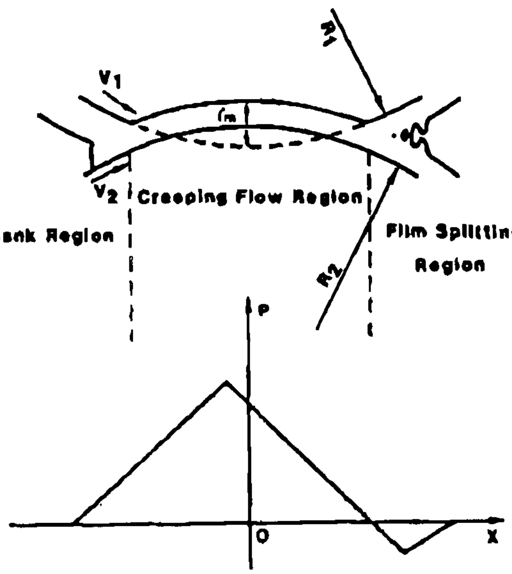

Figure 2 Printing nip flow and typical pressure profile of one rigid and one deformable roller (the original model is from that of banks and Mill).[9]

Film splitting mechanism

The ink film splitting geometries with low and high splitting speed are studied by (1) splitting between parallel flat plates; (2) splitting between a cylinder and a flat plate; (3) splitting between two cylinders.Two different approaches explained tack. It was suggested by Voet and Geffken[3] (1951) that tack is determined by the viscoelastic response of the inks toward rapid applied stress (force per unit area) which is studied under the geometry of splitting between a

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* Tensile stress is force per unit area in the direction normal to pressed surface.

cylinder and a flat plate. Banks and Mill[4] (1953), Strassburger[5] (1958) and Miller, Meyers, and Zettlemoyer[6] (1959), Taylor[7] (1959), and Erb and Hanson[8] (1960) proposed that tack is a consequence of cavitation and of the drop in hydrostatic pressure at the nip exit (Footnotes 4, 5, and 8 studied under the geometry of splitting parallel flat plates. Footnotes 6 and 7 studied under the geometry of splitting two cylinders). The significant information derived from previous work is that cavitation occurs and that there may be significant viscoelastic effects during actual separation or filament elongation. It is also apparent geometry plays an important part in the splitting process.

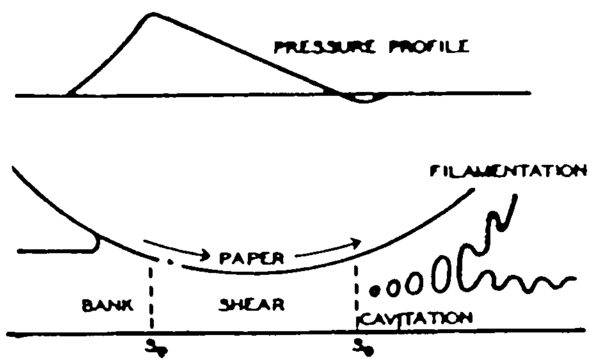


Figure 3 The suggested model of pressure profile and shear region in a press nip shown by Banks and Mill [9](1954), and Greener and Middleman[10] (1975)

The printing nip can be separated into three parts as shown in Figure 3. The finding that low shear measurements correlate with splitting behavior suggests that the splitting region in a nip is probably dominated by low rates of shear. The existence of low shear regions, indeed of no shear regions, in the nip has been confirmed by liquid film splitting studies conducted by the NPIRI rheology group[11] and by the NPIRI dispersion group.[12]

The pressure profile at the previous page shows[13] that the pressure is at a maximum at the beginning of the nip. This is a very important point because it had ever been previously thought that the pressure maximum is at the center of the nip. Electronic computer work showed that, when a 10 micron film is pushed down to 9.5 microns, the pressure rise may be as high as several hundred atmospheres. This pressure rise acts as a pump. This pumping action may explain why the leading edge of a print is usually sharper than the trailing edge.

A region of no shear is encountered at the pressure maximum. The pressure then drops across the nip, creating shear patterns. The shear, which is greatest where the pressure is falling the fastest, may reach the order of magnitude of 30,000 reciprocal seconds. The film pressure reaches a minimum at the end of the nip. This minimum pressure is about one atmosphere negative. A second plane of no shear is encountered here.

At the end of the nip where the plate and paper separate, the ink film can no longer fill the space between the cylinder and the plate. First cavities (or air bubbles) within the film form; these expand until filaments form and finally break. If the filaments break in two places, misting occurs.

The use of this model presented an aid in understanding the film splitting mechanism and its applicability to transfer and mottling results observed during the printing experiments.

Stefan equation in a printing nip

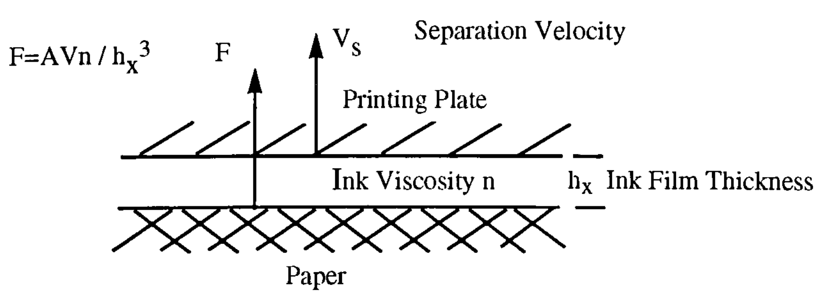
Stefan equation[14] was derived from studies of low viscosity Newtonian fluids (water, salt solution, alcohol, and air), at very slow separation velocities (about 0.01 mm/s), and at high film thickness (200 μm), much greater than those found in printing nips.

The Stefan equation expresses the stress F (force per unit area) needed to separate two plates immersed in a fluid, as a function of the separation velocity V_s of the two surfaces, the fluid viscosity n, the area A in contact, and the fluid thickness h_x between the two plates:

$$F = \frac{V_s n A}{h_x^3} \qquad (2)$$

Figure 4 illustrates the application of the Stefan equation as a model for the printing nip. In theories of fiber removal in the printing nip, the force applied to the paper surface is usually considered to be transmitted by ink tack.[15-19] Accordingly, ink tack ought to be measured by the maximum in the stress exerted on the paper surface by the ink, from the onset of cavitation in the ink film to the rupture of the ink filament.[15-17]

Figure 4 - Stress F applied on unit surface of paper by an ink film of viscosity n, and thickness h_x when the paper surface and the printing plate separate at a velocity V_s (according to Stefan equation). The paper and the printing plate are separated by an ink film thickness equivalent to the ink film thickness on the printing plate before printing. For simplification, absorption of ink at the paper surface is not considered.[20]



Velocity-Viscosity product

The product[21] of the printing speed Vp at which a fiber is picked from the paper surface and the viscosity n of the picking fluid is commonly known as the velocity-viscosity product, or VVP. In order to test a wide range of speed at one time, pick tests are usually performed in an accelerated mode of printing. The VVP concept was first proposed at the Institute of Paper Chemistry as a measure of the energy needed to debond a fiber from the paper surface.

$$VVP = V_p\, n \qquad (3)$$

The main reason for the choice of the VVP is that the units are those of energy per unit area (J/m^2). The VVP can also be expressed as a force per unit length (N/m) or the force required to debond a fiber of known length. In practical terms, the VVP permits the classification of paper as a function of picking resistance.

The numerical connection between the VVP and the actual maximum tensile stress (tack) in the film is not known, and it need not be known if the VVP may be taken directly as a measure of surface bonding strength. In the absence of a rigorous mathematical treatment of the problem, dimensional analysis can be applied, with the result that the stress should be proportional to the VVP and a function of the radius of the wheel and ratio of the film thickness to the radius. If the latter are held constant, the stress should be proportional to the VVP. If the bonding strength of a given paper is tested with oils having different viscosity, the observed VVP remains constant.

The relative basis in this study is that using the same paper with the same side if the picking velocity increases, the ink tack decreases and vice versa.

Deviations from the ideal relationship (VVP = constant) may be explained on the basis of experimental error, non-Newtonian behavior of the oil, the viscoelastic properties of the paper, and the thickness of the paper which causes the different geometries affecting the rate of separation at the parting surface of the ink film.[1 21]

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CHAPTER 3
REVIEW OF LITERATURE

Tack measurement

A variety of devices have been developed to measure ink tack. The most popular of these are the parallel plate tackmeter[1] (Green, 1941; Kelha *et al.*, 1973) and the Inkometer (Reed, 1973).

The parallel plate tackmeter is operated by pulling two plates apart by moving one of them perpendicularly against the plane surface (the more recently developing of the parallel plate tackmeter is shown in Footnote 2). However, parallel plate tackmeters do not simulate printing conditions, since the ink does not undergo shearing as it would in a printing nip. The Inkometer measures the displacement of a freely rotating rider roller caused by the splitting resistance of an ink film, which is continually split in the nip between the rider roller and the driving roller.

G.A.T.F developed the press Inkometer[3] to measure the dynamic condition of tack on the press. In addition, there are some research instruments used in the laboratories. LithLab System Fogra[4] is said to be able to measure wet tack (emulsified tack) under the defined conditions of ink amount, dampening solution, speed, and temperature. It is said the first direct measurement[5] of ink film splitting forces was carried out by Patel and Dealy (1987). A rotary laboratory printing press[6] using a pressure transducer manufactured to the radius of curvature of the printing cylinder of this press was used to directly measure the liquid pressure profiles.

Evaluation of the Inkometer

The Inkometer was originally developed by Reed[7] to simulate on a laboratory scale, the processes developed as ink flows through a printing roller nip. The essential feature of this type of tackmeter are illustrated in Figure 5. Cylinder B is motor driven at a constant speed, while cylinder C rotates and reciprocates along its axis to generate a homogeneous ink film. Stress is transmitted from cylinder B to cylinder A by the ink and results in a net force on cylinder A in the direction " R". The force in the " L " direction required to prevent the displacement of cylinder A is measured and is proportional to the Inkometer response.

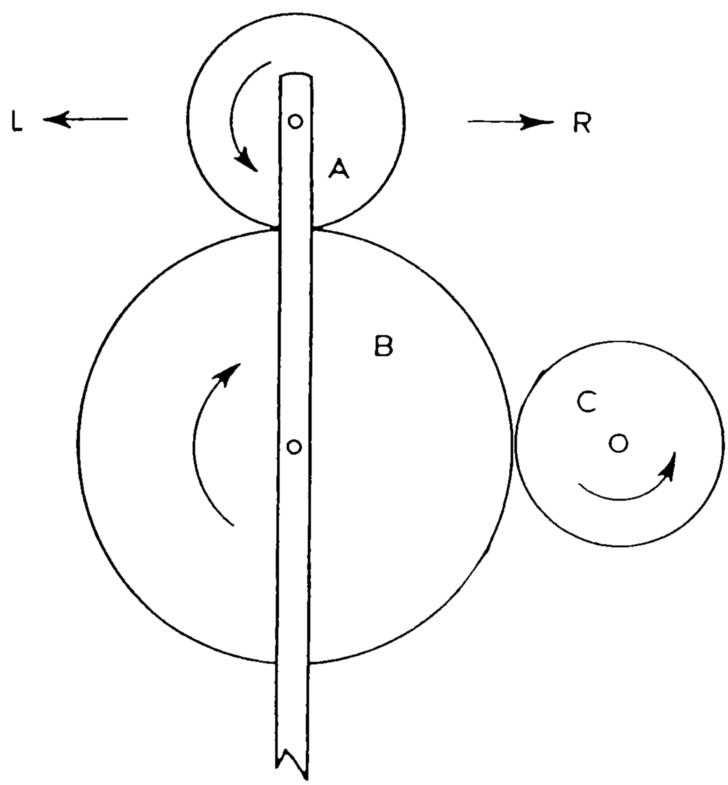


Figure 5 - Principal features of the Inkometer

The work of Mewis and Dobbels[8] reported that tackmeter of this type does not simulate the printing process. The force measured is strongly dependent on the loss tangent of the viscoelastic rubber covering cylinder A, and there is no way to scale-up tackmeter results so that they are quantitatively relevant to press behavior.[9] Furthermore, the measured data rather than the stress or energy involved in the splitting of ink films, a complex combination[10 11] of film splitting force, ink shortness ratio, ink elasticity, and viscoelastic properties of the rubber covering on the measuring roller is measured.

One defect presented by Lars H. Sjodahl [12] (1949) is that what an Inkometer measures is torque which is the product of two quantities; one is a pair of equal and opposite forces involved in film separation in which we are interested, the other, the distance separating these forces in which we are not interested. This distance is related to the width of contact between the top and brass rollers.

Factors affecting Inkometer response

Measurement of tack involves most of the rheological parameters and a geometry analogous to transfer process on the press. It provides a measure of the combined effect of the rheological properties, physical composition, and film splitting geometry on the actual force of separation. Because of the geometry of the film splitting process, the effects of pigment/vehicle interaction, pigment particle size and shape, pigment specific gravity, presence of air and solvent vapor bubbles, presence of bubbles of emulsified fountain solution all contribute in a major way to ink tack, along with the vehicle viscosity, shortness ratio and elasticity,[10] roller speed, surface temperature of ink film, ink film thickness, time for picking up the data[13] (relative to tack stability), blanket condition (absorption, thickness, hardness, steady-state condition,[14] and release force[15]).

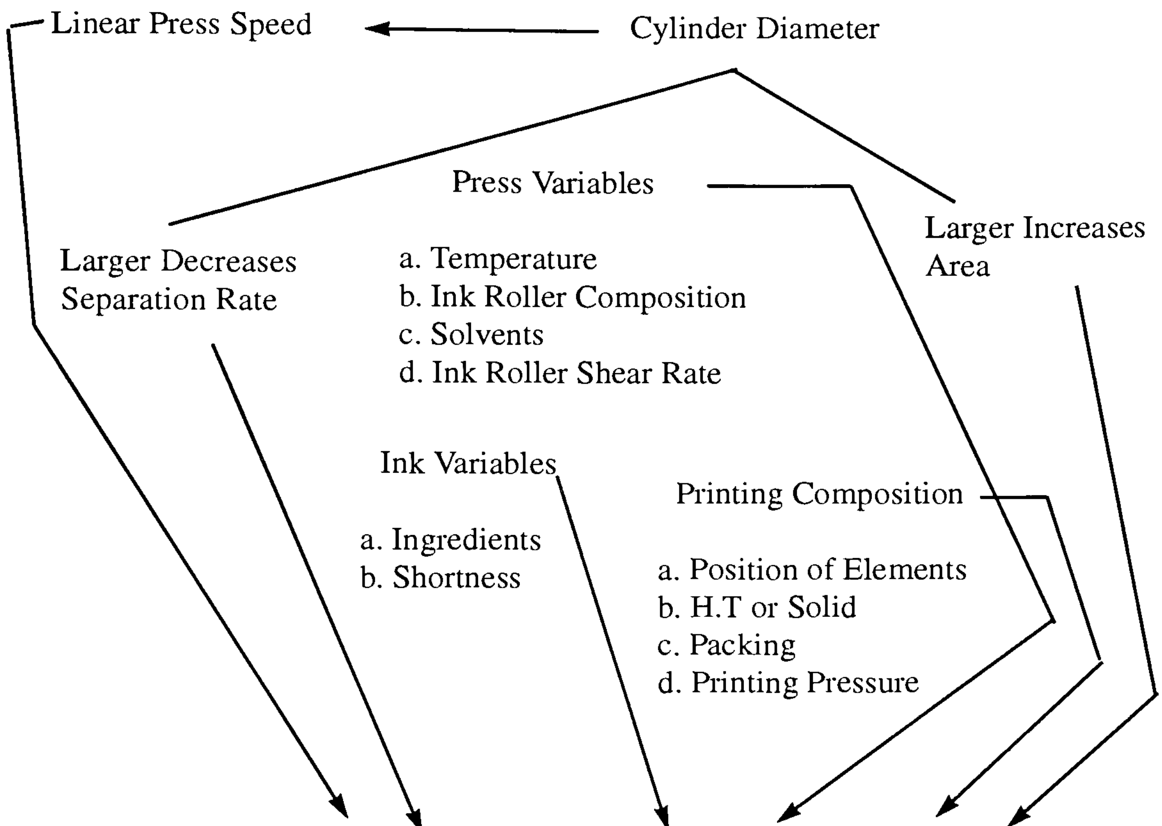
The mechanical Inkometers measure tack at specifc roller speeds[16] such as: 400 rpm (letterpress inks), 800 rpm (sheetfed offset inks), 1200 rpm (web offset inks), or 2000 rpm (new high speed web publication presses). The electronic version is more sophisticated and able to measure tack at any speed up to a maximum of 3000 rpm. Temperature is usually at a constant temperature, normally 90^0 F. Inkometer Pipette is used to control the ink amount which is usually about 1.32 cc.

One report[17] indicated that the ink film thickness measured on the Inkometer when the standard Inkometer volume metered by the Inkometer ink pipette is applied is much greater than that on the press. Both of the measurements were taken on the oscillators. A conversion table using the Inkometer in this study is shown in Table 1.

Table 1 Conversion Table

Amount of ink applied to Inkometer	Film thickness
.1 cc	1 μm*
.2 cc	2 μm
.3 cc	3 μm
.4 cc	4 μm
.5 cc	5 μm
.6 cc	6 μm
.7 cc	7 μm
.8 cc	8 μm
.9 cc	9 μm

* One μm is equal to 0.0001cm.



$$\text{Splitting Force} \approx \frac{(\textbf{Separation Velocity})\ (\textbf{Ink Viscosity})\ (\textbf{Splitting Area})}{(\textbf{Ink Film Thickness}^3)}$$

Figure 6 Factors affecting tack on presses*

Figure 6 presents the relative factors affecting tack on press and are classified by the Stefan's model.

Although Inkometer response is not a direct measurement of tack on press, it is still a very useful number demonstrably correlated with transfer to stock,[18] picking and wet trapping in multicolor printing.[19]

In the evaluation of linting on commercial offset press, most authors[20-25] agree that an increase in ink tack (as measured by the Reed Inkometer) results in more lint on the blankets.

* Figure 6 was done by Daniels, C. J. of T & E center of R.I.T.

Tests of surface strength of paper

Various devices have been developed to test the surface strength of paper. The IGT printability tester is one that exhibits certain features of the printing operation and is well used for both ink and paper testing. Other testers, like the LTF picking tester, and the more versatile Prufbau Printability Tester are also used in ink or paper testing.

The IGT printability tester is a laboratory apparatus in which the essential features of the operation of printing are under some measure of control. It consists of an ink distribution device and a press model. In the printing unit, the power is furnished by a pendulum or spring and in later models by electrical means. One has the choice of either printing with a constant speed or accelerating. In the case of the latter, the paper strip is calibrated along its length in terms of speed. Under controlled conditions of humidity and temperature, this instrument can be used to examine a whole variety of printing properties together with comparisons of ink and paper.

A pick test is performed in an accelerated mode. Therefore, shear rates, filament acceleration at the out-going side of the printing nip are not constant during the test.

The continuous change in viscosity when printing in an accelerated mode could explain the findings of Blokhuis and Tollenaar. They showed that the viscosity-velocity product (VVP) increased only two times when the ink viscosity increased 20 to 70 Pa·s instead of a 3.5 increases as predicted by the VVP theory.

Depending on ink chemistry, ink viscosity may change by 10% to 100% per 1^0 Celsius change in temperature.[32 33] It was found that fiber weight removed from the paper surface increased from 75% to 100% per degree Celsius decrease in temperature. Huge variation from the concept of VVP may be caused by temperature

Tack vs. ink film thickness

Kehla et al[34 35] showed that the tack stress measured by a parallel plate tackmeter decreased as a function of the fluid (Newtonian oils and non-Newtonian inks) film thickness, and increased as a function of the fluid viscosity. However, the stress did not decrease as a function of the cube of the film thickness, and did not increase linearly with the viscosity. Therefore, they concluded that the Stefan equation does not apply in the printing nip condition.

Furthermore, it has been shown that a high viscosity silicone was unable to cause picking of the paper surface while a polyisobutene oil of similar viscosity, would cause picking. This raises a question: if the Stefan equation can apply to picking in printing, according to the Stefan equation, tack (splitting force) increases with increased viscosity, therefore, whether ink tack is the sole contributor to fiber removal in the printing nip?

The other relative experiment[36] done by Y. H. Zang, J. S. Aspler used the tackmeter measuring pressure profiles of thin (3-14 μm) ink films under printing conditions. They defined the maximum tensile stress that the ink can withstand in the nip exit before splitting to be the tack of the ink. The tack of inks without dissolved polymer appears to be independent of film thickness. The tack of inks with dissolved polymer resin increases strongly with increased amount (thickness) of ink in the nip. This suggested that at high speed, ink tack is mainly characterized by the response of polymer molecules toward rapidly applied stress.

The conclusion of above experiment also challenge the cavitation-bubble expansion-film splitting mechanism (Banks and Mills, 1953, 1954), except at low speed, where ink tack decrease with increasing film thickness. The cavitation theory predicts that the tack of a liquid should decrease with increasing film thickness and pigment content.

The increase in tack with thickness of ink is consistent with the work of Voet and Geffken[37] (1951) (roller cylinder tackmeter) and with the observation[38] that Inkometer tack increases with increased ink film thickness (Pangalos, 1983).

Pangalos[38] (1983) also showed that at low speed (1.1 m/s) the tack reaches a maximum and then decreases with increasing fluid thickness. At high speed (3.5m/s), tack increases with fluid thickness. This would confirm the idea that at low separation speeds, splitting is governed by viscous behavior, as expected from Stefan equation. On the other hand, rapid film splitting occurs by the formation and rupture of ink filaments, which are characteristics of the viscoelastic response of the liquid toward rapid applied stress (Voet and Greffken,[37] 1951).

The equation[39] concerning the relationship between ink film thickness and tack is based on Inkometer response.

$$(\text{Tack}_{\text{maximum}})(1-e^{-qx}) = \text{Tack} \qquad (4)$$

Where x is the ink film thickness, and q is a constant.

Picking velocity vs. ink film thickness

Since the studies of picking at the Institute of Paper Chemistry (1949) established the fundamental rule[40] that the product of rupture velocity and the viscosity of ink --- viscosity velocity product (VVP) --- remains constant as long as printing pressure, ink film thickness and the quality of paper remain fixed, efforts have been made to evaluate the surface strength of the paper using this VVP.

In order to explain some experimental results from the original VVP concept, Voet,[41] Tollenaar,[42 43] and Fetsko et al[44] proposed that the VVP would be a function of the printing conditions. Considerations of the basic equation suggest that it is applicable only for Newtonian fluid such as mineral oils (Worth and Coupe[45], 1961). Most modifications of the VVP concern different values for the viscosity exponent.[41 42 43 44] Therefore, Tollenaar[43] (1958) and Fetsko et al[44] (1962) proposed a general form of the VVP as

$$VVP = V_p n^m \qquad (5)$$

Wink et al[45] (1952) studied the relation between the ink film thickness and the rupture velocity and obtained the curves shown in Figure 7.

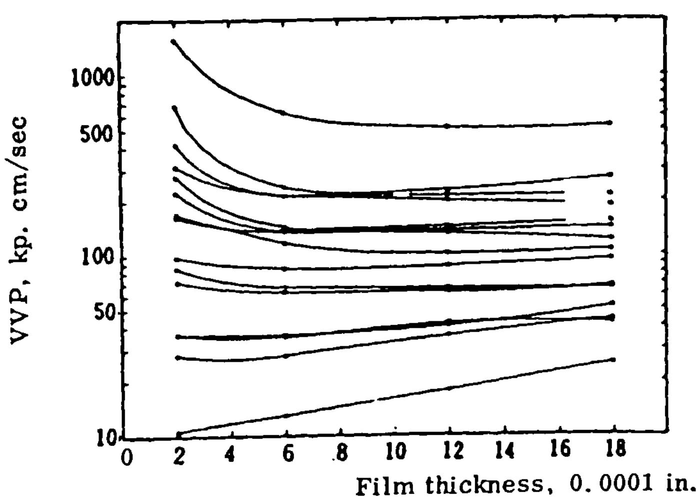


Figure 7 - The influence of the VVP on the thickness of the viscous film

Connell[46] (1955) represented the percentage of picking by the reflectance of the printed matter and obtained a curve as shown in Figure 8.

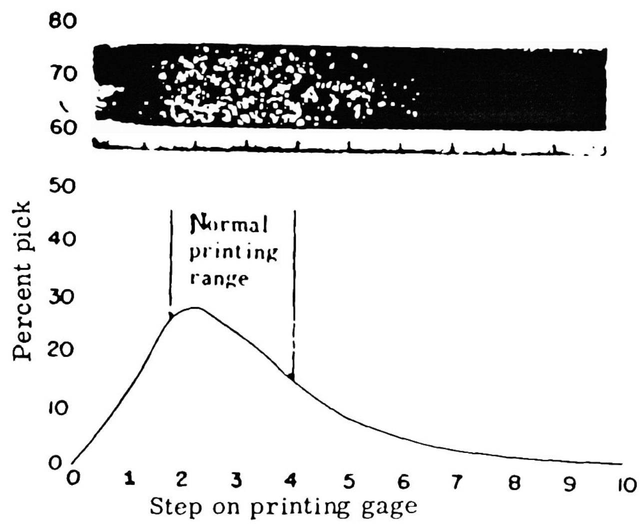


Figure 8 - Ink film thickness vs. picking

Fetsko et al[47] (1963) showed the same curve in their paper and assumed that the tail (to the right of the peak) of the curve satisfied the equation of Stefan. They concluded that the picking test should be performed at an ink film thickness at which this curve becomes flat.

Using the I.G.T printability tester, Blockhuis[48] (1963) tested the picking varying both printing pressure and ink film thickness, and obtained the curves shown in Figure 9. He explained that the percentage of picking decreased when the ink film thickness was below a certain value because of the incomplete contact of paper and ink.

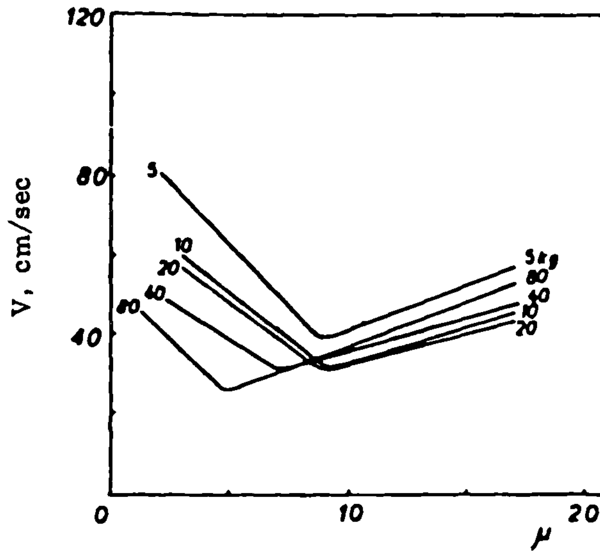


Figure 9 - Picking velocity vs. ink film thickness

Schirmer *et al* [49] (1959) studied the relation between ink film thickness and rupture velocity and obtained the curves shown in Figure 10.

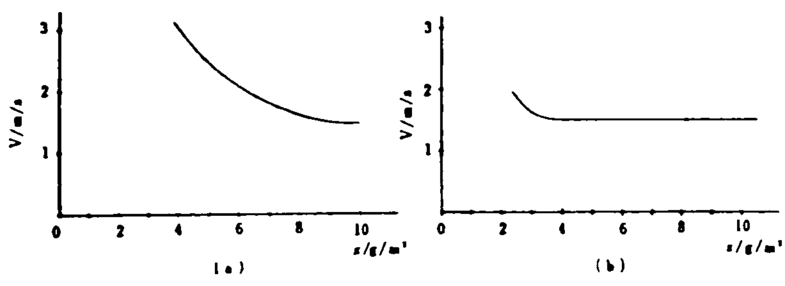


Figure 10 - Dependence of picking speed on ink film thickness

VVP vs. the Stefan equation

The Carlsson-Hultgren model

Carlsson and Hultgren[50] described the force acting on the paper surface using two components, one (F_2) parallel, and the second (F_4) normal to the paper surface.

$$F2,4 = \frac{K_{1,2}\ A\ V_p\ n}{h_x} \qquad (6)$$

where the parameter K1 and K2 a function of the paper properties and /or press geometry.

The Ide Model

With Newtonian oils of similar chemical composition, Ide[51] found that the pick force decreased linearly as the function of the ink film thickness after full coverage of the paper surface by the ink.

$$F = n^m\ V_p \quad Kh_x \qquad (7)$$

K is a function of the nip geometry, ink viscosity, and ink film thickness.

Summary of literature review

1. The measurements on the Inkometer are not direct measurements of tack. The Inkometer response is a complex physical combination[8 10] related to the real tack. The film thickness metered by the Inkometer ink pipette and applied on the Inkometer is much thicker than that on presses.[17] A large variety of factors were discussed and can cause change in the response.

2. The IGT Printability Tester is a model that simulates the condition created by presses. Using the accelerated velocity mode instead of the constant mode, the critical picking velocity can be found, which is determined on the paper strip that is calibrated along its length in terms of speed. Huge variation from the concept of VVP may be caused by temperature.

3. Various mathematical models[50 51] attempted to correlate the splitting force and ink film thickness. The tendency of picking velocity at different ink film thicknesses reverses when the paper is fully covered by inks.[48 51]

Comments on literature review

Since tack is not well defined and with some disagreement on instrumentation, the literature indicates contradictory conclusions related to tack. Some reported that this laboratory method is effective when correlated with that of the actual printing condition. All of them need to be justified by readers and further study is necessary.

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CHAPTER 4
STATEMENT OF THE PROBLEM

Lithographic ink tack is one of the most important properties that is presently a measurable quantity. Tack is also an ink characteristic, affecting the runnability and printability of paper. Inks of excessive tack may remove fiber or coating particles from the paper surface (picking and linting). In multicolor printing, both the initial tack and changes in tack during the fraction a second between the application of successive ink colors to the paper surface are important for ink setting and " trap " , or the ability of a wet ink film to accept another ink film on top of itself. Too low a tack can produce a variety of problems within the ink roller train right through to final print quality (dot gain, trapping, and roller slippage, inadequate ink feed, and distribution).

Experimental results[1] [3] shown by previous studies indicated increasing ink film thickness also increased ink tack on Inkometers. On the other hand, the practical experience[4] in the pressroom reported that the first down ink with a thick film can not get good trap when the second down ink with a thin film, eventhough the author thinks a thick ink film thickness has a higher tack than a thin ink film thickness. If the theory[5-9] of fiber removal in the printing nip, the force applied to the paper surface to be transmitted by ink tack is correct, and if the the Inkometer response[10-17] is a very useful number when correlated with transfer to stock, picking, and wet trapping in multicolor printing is also correct, a study of how the Stefan equation can apply to the printing condition or what the relationship of ink film thicknesses and ink film splitting forces are, could be investigated at least in two ways. One is on an Inkometer which is representative of the ink transfer or ink distribution section on the presses. The other is on IGT Printability Tester which is representative of the printing section on a press. It is assumed that the Inkometer and IGT Printability Tester are good mechanical models of actual printing conditions. On the other hand, the material used to generate the Stefan equation are Newtonian fluids and a non-absorbent substrate that is quite different from the situation in printing.

In the context of the above discussion, the research questions developed were intened to investigate whether the Stefan equation can apply to printing.

Is there significant effect due to ink film thickness on ink tack as measured by an Inkometer? Is there any significant effect due to film thickness of Newtonian and non-Newtonian fluids on picking velocity when using the IGT Printability Tester? Is there significant effect due to thickness of the first down ink film on ink trapping with absorbent and non-absorbent substrates in the simulated condition provided by the IGT Printability Tester?

Null hypotheses and alternative hypotheses

H_{01}: There is no significant effect due to vegetable-oil-based ink film thickness on ink tack as measured by an Inkometer.

H_{11}: There is significant effect due to vegetable-oil-based ink film thickness on ink tack as measured by an Inkometer.

H_{02}: There is no significant effect due to film thickness of oil-based fluid on picking velocity under the proposed experimental design on the IGT Printability Tester.

H_{12}: There is significant effect due to film thickness of oil-based fluid on picking velocity under the proposed experimental design on the IGT Printability Tester.

H_{03}: There is no significant effect due to the first down vegetable-oil-based ink film thickness on ink trapping capability under the proposed experimental design on the IGT Printability Tester.

H_{13}: There is significant effect due to the first down vegetable-oil-based ink film thickness on ink trapping capability under the proposed experimental design on the IGT Printability Tester.

Limitations

I. It is assumed that ink tack measured by an Inkometer relates to actual use on printing presses.

II. It is assumed that the force applied to the paper surface to remove fibers or coatings is transmitted by tack.

III. It is assumed that the force applied to the ink film surface to pull ink is transmitted by ink tack during the trapping.

IV. Printing conditions are well simulated by the Inkometer and IGT Printability Tester used in this experiment.

V. It is assumed that it is suitible to use the accelerated velocity mode in the IGT Printability Tester.

Delimitations

I. Other temperature and operating speeds for measurement of ink tack were not studied because the effect of these variables are not in question.

II. Ink film thickness less than .6 or more than 5.4 was not studied. This range is expected to cover the full practical range of ink film thickness.

III. The VVP concept was not investigated.

IV. Gravimetric trapping is the better way to measure the physical trapping percentage.

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CHAPTER 5

METHODOLOGY

Experimental design

This study was separated into three experiments. An Inkometer was used in the first experiment. The second and third are accomplished with the IGT Printability Tester.

Two black vegetable-oil-based inks (low and high level tack) obtained by the T & E Center at R.I.T. were used for all of the three experiments. An IGT standard oil (low viscosity) was also used in the second experiment. One paper provided by the T & E Center was used in the second experiment. Another paper stock and one plastic substrate also from the T & E Center at R.I.T. were used in the the third experiment.

The experiment using the Inkometer is a two times replicated three factor design. The inks at high and low tack is factor A. The second factor examined was ink film thickness. The tested levels were .6, 1.8, 3.0, 4.2, and 5.4 µm. The third factor was time. The Inkometer response was sampled at 1, 5, and 10 minutes. These levels (Table 2) produce a total of thirty individual treatments. Two replicates of each treatment were prepared; 30 treatments x 2 replicates = 60 measurements of ink tack. The temperature was fixed at 90^{0} F. The cylinder speed was fixed at 800 rpm.

Table 2 - The layout of the first experiment on the Inkometer

Inkometer response		Ink Film Thickness														
		.6 µm			1.8 µm			3.0 µm			4.2 µm			5.4 µm		
		Time														
		1'	5'	10'	1'	5'	10'	1'	5'	10'	1'	5'	10'	1'	5'	10'
Ink	Low	-												-	-	
	High	-		-											-	

The second experiment of this study on the IGT Printability Tester was a twice replicated two factor experiment with picking velocity as the response variable. The first factor are fluids at three levels (two inks and the IGT standard oil.) The second factor is ink film thickness at the same levels used in the first experiment. These levels (Table 3) produce a total of fifteen individual treatments. Two replicates of each treatment are prepared; 15 treatments x 2 replicated = 30 responses for this experiment. The paper used was provided by the T & E Center at R.I.T. The printing force was fixed at 40kgF. The accelerated mode was employed, and was fixed at 5m/s maximum velocity.

The third experiment using the IGT Printability Tester was a twice replicated three factor design to measure the gravimetric trapping. Two inks at high and low ink tack is factor A. Factor B was the ink film thickness of the first down ink. The levels tested were .6, 1.8, 3.0, 4.2, and 5.4 μm. Factor C is a paper and plastic substrate. This experiment shown by Table 4 produces a total of twenty individual treatments. Two replicates of each treatment were prepared; 20 treatments x 2 replicates = 40 responses for gravimetric trapping. The ink film thickness (on the printing disc) second down the paper was fixed at about 3.5 μm. The velocity was fixed at 1.6 m/s with the instrument set at constant velocity. The printing force was fixed at 40kgF.

Table 3 - The layout of the 2nd section

Picking Velocity			Ink Film Thickness				
			.6 μm	1.8 μm	3.0 μm	4.2 μm	5.4 μm
Fluid	Ink	Low	-				
		High	-			-	
	IGT Oil		-	-	-		

Table 4 The layout of the 3rd section

Gravimetric Trapping			Ink Film Thickness				
			.6 μm	1.8 μm	3.0 μm	4.2 μm	5.4 μm
Substrate	Paper	Ink: High					
		Low		-			
	Plastic	High			-		-
		Low				-	

Instrument, accessaries, and material used

The Inkometer Lithographic Technical Foundation, Inc., patent no. 2, 101, 322, under license by THWING-ALBERT INSTRUMENT COMPANY with the ink pipette. The total area of the rollers (top roller, metal roller, and distribution roller) is $1031.81 cm^2$.

The IGT Printability Tester The type AIC2-5 electrically driven printability tester, the inking unit, printing discs, ink pipette (accuracy to $0.01\ cm^3$), pick start viewer, and IGT oil. On the inking unit, the total area of the rollers for the configuration of the 2 cm printing disc is $1248.38 cm^2$, for the configuration of the 5 cm printing disc is $1313.18\ cm^2$.

The Mettler Analytical Balance Capacity to 160 grams; accuracy to 0.0001 grams.

The inks and IGT oil Two vegetable-oil-based sheetfed black inks, one with a specific gravity $1.07596\ g / cm^3$ and a higher tack (20.5 - 1st min./ 800 rpm/ 90 degree F/ standard amount), the other with a specific gravity $1.08780\ g / cm^3$ and a lower tack (17.2 - 1st min./ 800 rpm/ 90 degree F/ standard amount) by the same manufacturer, the low viscosity IGT oil with a specific gravity $0.6070\ g / cm^3$.

The paper C2S were selected. For the second experiment a $45.7251\ g / m^2$ basic weight, 0.0017-inch thickness, and 1.36 μm roughness was used. The third experiment made use of paper having a $73.6251\ g / m^2$ basic weight, 0.0024-inch thickness, and 1.26 μm roughness.

The plastic substrate The regular plastic stripping film was used. This is a 0.007 inches mylar sheet material.

Fixed experimental procedures and methods used

Three experimental sections on the Inkometer or IGT Printability Tester were controled by fixed procedures and methods.

Tack measurement on the Inkometer

1. The time for warming up the Inkometer was 30 minutes. The objective here was to attain a temperature of 90 degree F. Then the instrument was calibrated by adjusting zero with no ink on the rollers and the maximum reading of 25 using the appropriate calibrating bar.

2. The control ink was used (a news transparent white provided by Mr. Hart Swisher) to condition the roller surface for 5 minutes, after which it was then cleaned up. The Inkometer was tested to determine whether or not it was in control. The reading was relatively stable at 6.5 (1st min./standard volume applied/ 800 r.p.m./ 90 degree F) for a week of preliminary tests. All experimental data was recorded until the control ink's reading under the same condition was 6.5.

3. Conditioning the roller surface with the ink tested was performed. Before operating the Inkometer, the ink that was applied was spread for 10 seconds by manually operating the instrument.

4. The distribution roller (oscilator) was at the central position before starting. This made the ink film distribute more uniformly.

5. Between any two succeeding experimental readings, the re-calibration was replaced by plus or minus the difference (from zero which is no ink on the Inkometer) on the reading in order to maintain the same mechanical basis.

6. The laboratory ambient temperature was 21 degree Celsius.

Picking and trapping experiments on the IGT Printability Tester

The inks tested on the inking unit and printing discs were metered and timed to maintain consistency. The time for inking was set at 2 minutes. The room temperature was 21 degree Celsius.

Determining the Ink film thicknesses

Weighing was the method used to obtain the five ink film thicknesses. The followed physical formula was used to find thickness,

$$\text{Thickness (cm)} = \frac{\text{Weight (g)}}{\text{Density}(\text{g} / \text{cm}^3) \times \text{Area (cm}^2)}$$

five ink film thicknesses were used for this study.

The weight of the ink was measured by the Mettler Analytical Balance (capacity to 160 grams, accuracy to 0.0001 grams). The weight of the two black inks and the IGT oil versus the film thicknesses in the three experiments is shown in Table 5-11.

The specific gravity (density) of the high and low tack ink was 1.07596 g / cm^3 and 1.08780 g / cm^3 respectively. The total area of the rollers of the Inkometer was 1031.81 cm^2.

Table 5 Experiment 1 (the low tack ink)

Weight	Thickness
0.0673 g	0.000059961 cm ≈ 0.6 μm
0.2020 g	0.000179971 cm ≈ 1.8 μm
0.3367 g	0.000299981 cm ≈ 3.0 μm
0.4714 g	0.000419992 cm ≈ 4.2 μm
0.6061 g	0.000540002 cm ≈ 5.4 μm

Table 6 - Experiment 1 (the high tack ink)

Weight	Thickness
0.0666 g	0.00005999 cm ≈ 0.6 μm
0.1998 g	0.00017997 cm ≈ 1.8 μm
0.3330 g	0.00029995 cm ≈ 3.0 μm
0.4662 g	0.00041993 cm ≈ 4.2 μm
0.5994 g	0.00053991 cm ≈ 5.4 μm

In reviewing the above one might ask if there is a significant difference of thickness at each level between the two inks that are shown. In this regard, the author investigated the minimum difference of film thickness at each thickness level that would cause a change in Inkometer response. This minimum was equal for both inks from 0.6 to 5.4 μm is about 0.1 to 0.3 μm. The differences of the film thicknesses between the two inks at each level were within the above range.

The specific gravity of the IGT oil was 0.6070 g / cm^3. The total area of the rollers of the IGT inker was 1248.38 cm^2.

Table 7 Experiment 2 (the low tack ink)

Weight	Thickness
0.0815 g	0.000060015 cm ≈ 0.6 μm
0.2445 g	0.000180046 cm ≈ 1.8 μm
0.4075 g	0.000300076 cm ≈ 3.0 μm
0.5705 g	0.000420107 cm ≈ 4.2 μm
0.7335 g	0.000540137 cm ≈ 5.4 μm

Table 8 Experiment 2 (the high tack ink)

Weight	Thickness
0.0806 g	0.000060006 cm ≈ 0.6 μm
0.2418 g	0.000180017 cm ≈ 1.8 μm
0.4030 g	0.000300028 cm ≈ 3.0 μm
0.5642 g	0.000420040 cm ≈ 4.2 μm
0.7254 g	0.000540051 cm ≈ 5.4 μm

Table 9 Experiment 2 (the IGT oil)

Weight	Thickness
0.0455 g	0.000060045 cm ≈ 0.6 μm
0.1364 g	0.000180003 cm ≈ 1.8 μm
0.2273 g	0.000299960 cm ≈ 3.0 μm
0.3128 g	0.000419918 cm ≈ 4.2 μm
0.4091 g	0.000539876 cm ≈ 5.4 μm

The investigation of the thinnest film thickness required to cause a change in the picking velocity response for each level of the three fluids was between 0.25 to 0.45 μm. The difference of the film thicknesses between each two fluids at each level was within the above range.

In the third section, the total area of the rollers for the first down ink was 1313.18 cm^2. The area of the first disc was 5 x 21.6 = 108 cm^2. The total area of the rollers for the second down ink was 1248.38 cm^2. The ink film thickness of the second down ink was maintained at 3.5 μm. This was obtained by metering out 0.4753 g (low tack ink), and 0.4701 g (high tack ink). This amount of ink produced thicknesses of 0.000350003 cm and 0.000349983 cm. It was assumed that the difference between the second down ink film thickness of the low and high tack inks would not affect the trapping significantly.

Table 10 - Experiment 3 (the low tack / trapping)

	Weight	Thickness
Paper	0.0069 g	0.000058732 cm = 0.58732 µm
	0.0215 g	0.000183006 cm = 1.83006 µm
	0.0352 g	0.000299619 cm = 2.99619 µm
	0.0493 g	0.000419637 cm = 4.19637 µm
	0.0634 g	0.000539655 cm = 5.39655 µm
Plastic	0.0071 g	0.000060435 cm = 0.60435 µm
	0.0211 g	0.000179601 cm = 1.79601 µm
	0.0352 g	0.000299619 cm = 2.99619 µm
	0.0494 g	0.000420489 cm = 4.20489 µm
	0.0635 g	0.000540506 cm = 5.40506 µm

Table 11 - Experiment 3 (the high tack ink / trapping)

	Weight	Thickness
Paper	0.0070 g	0.000060239 cm = 0.60239 µm
	0.0209 g	0.000179857 cm = 1.79857 µm
	0.0348 g	0.000299474 cm = 2.99474 µm
	0.0487 g	0.000419092 cm = 4.19092 µm
	0.0626 g	0.000538709 cm = 5.38709 µm
Plastic	0.0075 g	0.000064542 cm = 0.64524 µm
	0.0202 g	0.000173833 cm = 1.73833 µm
	0.0350 g	0.000301195 cm = 3.01195 µm
	0.0490 g	0.000421673 cm = 4.21673 µm
	0.0629 g	0.000541291 cm = 5.41291 µm

The lowest ink film thickness to significantly change the trapping response at each level of the two inks and the two substrates was between 0.1 µm and 0.2 µm. The differences of the ink film thickness at each level between the two inks and substrates were within the above range.

Configuration of the IGT Printability Tester for trap testing

Two different printing discs, one with a 2 cm width and the other 5 cm's wide and a circumference of 21.6 cm were used in the trapping experiment. The 5 cm disc was positioned on the upper shaft for the first ink printed, and the 2 cm disc was positioned on lower shaft for the second print. The trapping portion of the second print was totally within the the first print because the width of the first print was wider than that of the second print. The printing length of the two prints were totally equal to the circumference of the discs respectively. This meant that no portion of either disc was printed twice. This special configuration is shown in Figure 11.

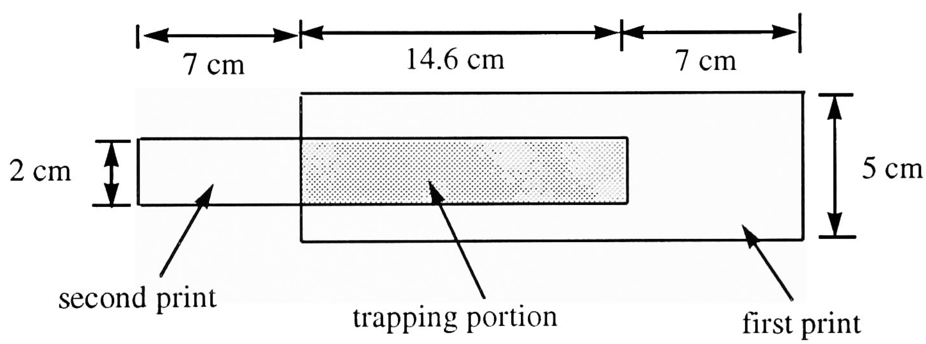

Figure 11 The configuration of the trapping

Calculation of ink trapping by the gravimetric method

Gravimetric trapping is calculated by dividing the ink film thickness of the second ink (IFT_2) that is on top of the first ink by the ink film thickness that is printed directly on substrate (IFT_1).

The ink film thickness is calculated by dividing the weight of ink by the product of the specific gravity of the ink and the area printed with the ink. In calculating the weight of the second ink on top of the first ink layer, the weight of the area of the second ink printed directly to substrate is subtracted from the total weight of the ink transferred from the disc. In some related studies, it is assumed that the ink split 50 / 50 when it is transferred to the paper. However, It might be better to measure it directly. The experimental data (Table 12) shows different transfer ratio at 3.5 μm on the printing disc under the experimental printing system involving the two black inks and the paper and plastic substrate with the specific printing force and speed specified in the experimental design. As a result, according to the above ink transfer ratio, from which IFT_1 could be known, the weight of the ink transferred directly to the substrate was a portion of the total weight of the ink on the disc, multiplied by a ratio of the area of the ink on the substrate and the total area of the ink on the disc. The actual weight of the ink printed on the top of the first ink was then converted to IFT_2. One sample to calculate the gravimetric trapping is shown in Appendix B.

Table 12 - The ratios of the inks directly transferred to substrate

	Low tack ink	High tack ink
Paper	0.54	0.48
Plastic film	0.42	0.45

CHAPTER 6

ANALYSIS OF DATA AND RESULTS

The purpose of this study was to find the relationship (not mathematical) between ink tack and ink film thickness at thicknesses between 0.6 to 5.4 μm . The null and alternative hypotheses have been stated. The experimental data are listed in Appendix C. They are tested by ANOVA (analysis of variance) with the $\partial = 0.05$ / two-sided. Regression analysis is used to discover the tendency of change in ink tack with change in ink film thickness between the thickness 0.6 to 5.4 μm with the three types of measurements. Observation for consistency among experiments 1, 2, and 3 was accomplished by graphing the data.

In the ANOVA, if the null hypothesis is rejected, the variance of among groups is greater than that of within groups and is indicated an F statistic is equal or greater than the critical value F. The three null hypotheses are rejected at a level of significance 0.05 / two-sided by significant difference between the F statistic and F critical values ($F_{statistic} > F_{critical}$). There is signifcant effect due to ink film thickness on ink tack as measured by an Inkometer; there is a significant effect due to film thicknesses of fluids on picking velocity under the proposed experimental design on the IGT Printability Tester; and there is a significant effect due to the first down ink film thickness on ink trapping capability under the proposed experimental design on the IGT Printability Tester. The ANOVA tables are shown in Table 13. According to the ANOVA, additional comments are appropriate.

When evaluating regression analysis, R^2 (coefficient of determination) determines the proportion of variability in y (response) that is explained by the mathematical model under test; R^2 is computed for the experimenter to estimate whether a regression equation will be useful for predicting y.

In experiment 1 (Inkometer section,) the Inkometer response was shown to increase when the ink film thickness increased. This is limited to the thicknesses tested (0.6 to 5.4 μm) at each ink level (high and low) and each time interval at which the data was obtained (1', 5', and 10'). This observation indicates ink tack increases when the ink film thickness increases. This is not in agreement with the Stefan equation. The graphs of data and the regression analysis are shown in Appendix D-1 to D-6.

In experiment 2 (pick testing on the IGT Printability Tester), the critical picking velocity increases with ink film thicknesses from about 3.0 μm up to 5.4 μm, and decreases with ink film thicknesses thinner than 3.0 μm down to 0.6 μm at both of the low and high inks' levels. This suggests tack (splitting force) increases when the ink film thickness increases from 0.6 to around 3.0 μm, and then decreases when the ink film thickness rises to about 3.0 μm to 5.4 μm. The first half of the results of this experiment does not agree with the Stefan equation. When using the IGT oil, the critical picking velocity decreases with increase in film thicknesses over the range of thicknesses tested (0.6 to 5.4 μm.) That means the tack (splitting force) increases when the Newtonian fluid film thickness increases from 0.6 to 5.4 μm. This is in contradiction to the Stefan equation. The graphs, regression equations, and R^2 are shown in Appendix D-7 to D-9.

Experiment 3 (gravimetric trapping on the IGT Printability Tester), indicates that gravimetric trapping increases when the ink film thickness decreases at both ink levels (low and high) and on two different substrate levels (paper and plastic film.)

This is interpreted to indicate that the ink tack increases when the ink film thicknesses decrease from 5.4 μm to 0.6 μm. This is in general agreement with the Stefan equation. Graphs of the data, regression equations, and R^2 are shown in Appendix D-10 to D-13.

In summary, three experiments have been accomplished and examined. The three types of responses show inconsistency in the relationship between ink tack and ink film thickness. This may be the reason for the inconsistency shown by the literature.

There is a statistical association between the Inkometer response and gravimetric trapping for ink film thicknesses 0.6 to 5.4 μm. This is the only simple association that is found here between two types of measurements. Within 0.6 to 5.4 μm, gravimetric trapping decreases when the Inkometer response increases (Appendix E).

The ANOVA (Table 13) indicate additional results. The ink tacks (low and high levels) specified by the manufacturer and time show a significant effect on the Inkometer response. This shows that time and ink tack also affect the Inkometer response within the film thicknesses from 0.6 to 5.4 μm. On the other hand, in experiment 3, the substrates could affect the gravimetric trapping with the two inks in this study within ink film thicknesses of 0.6 to 5.4 μm.

Table 13 ANOVA tables

Experiment 1:

Source	DF	SS	MS	$F_{statistic}$	$F_{critical}$
Ink	1	198.744	198.744	2735.01	5.568
Time	2	12.306	6.153	84.68	4.182
IFT	4	1123.108	280.777	3863..91	3.250
Ink*Time	2	71.397	35.698	491.26	4.182
Ink*IFT	4	82.358	20.589	283.34	3.250
Time*IFT	8	21.014	2.627	36.15	2.651
Ink*Time*IFT	8	9.556	1.195	16.44	2.651
Error	30	2.180	0.073		
Total	59	1520.663			

Experiment 2:

Source	DF	SS	MS	$F_{statistic}$	$F_{critical}$
Fluid	2	1.489	0.744	63.28	4.765
IFT	4	0.971	0.243	20.63	3.804
Fluid*IFT	8	1.112	0.139	11.81	3.199
Error	15	0.176	0.012		
Total	29	3.748			

Experiment 3:

Source	DF	SS	MS	$F_{statistic}$	$F_{critical}$
Substrate	1	0.251	0.251	76.42	5.871
Ink	1	0.011	0.011	3.21	5.871
IFT	4	5.926	1.482	450.67	3.515
Substrate*Ink	1	0.006	0.006	1.83	5.871
Substrate*IFT	4	0.227	0.057	17.30	3.515
Ink*IFT	4	0.009	0.002	0.69	3.515
Substrate*Ink*IFT	4	0.035	0.009	2.64	3.515
Error	20	0.066	0.003		
Total	39	6.531			

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

The purpose of this study was to investigate the relationship between ink film splitting forces and ink film thicknesses between the thicknesses from 0.6 to 5.4 μm, and determine if there is agreement with the Stefan equation. A review of the literature indicates a lack of universal agreement in this regard. The research environment including splitting geometry, splitting velocity, film thickness, material, direct or indirect measurement used for studying the film splitting force are probably major reasons for this disagreement.

The Inkometer and IGT Printability Tester used in this study are two mechanical models that simulate actual press conditions. The three types of measurements, Inkometer response, picking velocity, and gravimetric trapping, are related to ink film splitting force to investigate the relationship between ink film splitting forces and ink film thicknesess.

The null hypotheses studied are the following.

H_{01}: There is no significant effect due to vegetable-oil-based ink film thickness on ink tack as measured by an Inkometer.

H_{02}: There is no significant effect due to film thickness of vegetable-oil-based fluid on picking velocity under the proposed experimental design on the IGT Printability Tester.

H_{03}: There is no significant effect due to the first down vegetable-oil-based ink film thickness on ink trapping capability under the proposed experimental design on the IGT Printability Tester.

Analysis of Variance indicates that the null hypotheses shown are rejected. Ink film thickness does affect the Inkometer responses, film thickness does affect the critical picking velocity, and has an effect on gravimetric trapping, within the film thicknesses' range from 0.6 μm to 5.4 μm.

1. The inkometer tack increases with increased ink film thickness. This contradicts the prediction of the Stefan equation.

2. Below a certain value of ink film thickness, when ink film thicknesses increase the ink tack increase then decrease above that value of ink film thickness. This was shown by the picking response on the IGT Printability Tester. This is partially in contradiction to the Stefan equation and partially in agreement.

3. With the IGT oil (a Newtonian fluid), the tack increased with increased IGT oil film thicknesses.

4. Ink film splitting force increased when the ink film thicknesses decreased. This is shown by gravimetric trapping and accomplished by the use of the IGT Printability Tester on paper and plastic substrates. The Stefan equation was not rejected when it is applied to the gravimetric trapping.

5. The relationship between ink film splitting forces and film thicknesses among experiments was not consistent. This suggests further study. It implies whether the Inkometer response could predict the performance of the vegetable-oil-based inks within the pratical ink film thicknesses on presses.

I. Since the tack has a cohesive and adhesive property, the study of the contact surface is necessary, such as the splitting force established between metal and rubber, ink film and paper, and ink film and ink film.

II. The more accurate way to investigate the Stefan equation would be a direct measurement of the splitting force with the consideration of the comparison of the parallel and roller's splitting geometries, low and fast speeds, thin and thick film thicknesses, Newtonian and non-Newtonian fluids, and absorbent and non-absorbent substrates.

III. According to the data in Appendix C, table 14, the high tack ink's tacks (all the replications) are lower than those of the low tack ink's tacks within the ink film thicknesses of 0.6 to 3.0 µm at each time level. The studies of Inkometer response of thin ink film thicknesses are necessary.

IV. When one evaluates the association of the IFT vs. the gravimetric trapping (Appendix D-10 ~ D13), since the range of ink film thickness from 0.6 to 5.4 µm is quite narrow on the Stefan equation. The linear regression model from the ink film thickness 0.6 to 5.4 µm might be a portion of the Stefan equation's steep part (thin films) which is almost mathematically like a line, and it is suggested for further study. In Appendix D10 ~ D13, R^2 of the linear and polynomial regression equations show high values (above 0.95); both of the linear and polynomial regression equations are reliable. For the practical use in production, if a linear model could be applied to predict responses without significant differences compared with a more complicated mathematical model, that linear model does not need to be held.

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Appendices

Appendix A

Raw data of weight (g) of ink transferred from discs

Appendix A - The raw data of the weight (g) of ink transferred from discs

	Substrate			
	Paper		Plastic film	
	Ink			
	Low	High	Low	High
0.6 µm	0.0115	0.0095	0.0110	0.0109
	0.0109	0.0101	0.0107	0.0107
1.8 µm	0.0098	0.0091	0.0088	0.0089
	0.0094	0.0082	0.0090	0.0088
3.0 µm	0.0083	0.0073	0.0070	0.0075
	0.0086	0.0068	0.0066	0.0081
4.2 µm	0.0072	0.0063	0.0057	0.0058
	0.0067	0.0057	0.0059	0.0062
5.4 µm	0.0062	0.0053	0.0044	0.0045
	0.0060	0.0051	0.0046	0.0046

Appendix B

Calculating ink trapping by gravimetric method

Appendix B - Calculating ink trapping by gravimetric method

(data from Appendix A / Paper / Low tack ink / the first replication)

Specific gravity of the low tack ink: 1.08780 g / cm^3

Printed area: 21.6 x 2= 43.2 cm^2

" disc 2 " refers to the printing disc with which the second-down ink is printed.

weight of disc2	=154.5355 g
weight of disc2 + ink	=154.5519 g
weight of ink on disc2	=154.5519 - 154.5355 g
before transfer	=0.0164 g
ink film thickness on disc2	=weight / specific gravity / area
	=0.0164 / 1.08780 / 43.2
	=0.000348988 cm
weight of disc2	
after transferred	=154.5404 g
weight of ink transferred	=154.5519 154.5404 g
	=0.0115 g
area of ink transferred	
directly to paper	=14 cm^2
weight of ink transferred	
directly to paper	= (ink transfer ratio) x (weight of ink on disc2) x (area of coverage on paper / total area of coverage)
	=0.54 x 0.0164 x (14 / 43.2)
	=0.0029 g

ink film thickness of ink transferred to paper directly as derived from ink transfer ratio	=0.000188454 cm
weight of ink2 printed on top of ink1	=0.0115 - 0.0029 =0.0086 g
area of ink2 overprinted on ink1	=29.2 cm
ink film thickness of ink2 printed on top of ink1	=0.0086 / 1.08780 / 29.2 =0.000270749 cm
% gravimetric trapping	=0.000270749 / 0.000188454 =143 %

Appendix C

Experimental data

Appendix C - Experimental data

Table 14 - Data on the Inkometer (Inkometer response is a complex physical combination, so the data are not proposed with a unit.)

		0.6 μm		**1.8 μm**		**3.0 μm**		**4.2 μm**		**5.4 μm**	
	1 min.	8.5	8.5	13.0	13.2	14.6	14.5	15.5	15.4	16.5	16.5
Low Tack Ink	**5 min.**	8.5	8.5	13.7	13.8	15.5	15.7	17.0	17.1	18.2	18.5
	10 min.	8.5	8.5	14.1	14.3	16.2	16.3	18.0	18.0	19.0	19.5

		0.6 μm		**1.8 μm**		**3.0 μm**		**4.2 μm**		**5.4 μm**	
	1 min.	4.9	4.5	10.2	10.5	14.3	14.0	16.8	16.2	17.5	17.0
High Tack Ink	**5 min.**	2.2	1.8	6.7	7.0	12.3	11.5	16.8	16.3	18.4	18.3
	10 min.	1.5	1.1	4.1	4.8	8.5	8.3	14.2	13.3	16.7	16.2

Table 15 Data of picking velocity (m / s) on the IGT Printability Tester

	0.6 μm	**1.8 μm**	**3.0 μm**	**4.2 μm**	**5.4 μm**
Low tack	2.50 2.72	2.28 2.28	2.06 2.06	2.28 2.50	2.50 2.72
High tack	2.06 2.06	1.81 1.81	1.59 1.59	2.06 2.28	2.28 2.50
IGT oil	2.50 2.28	1.81 2.06	1.81 1.81	1.59 1.59	1.59 1.59

Table 16 - Data of gravimetric trapping on the IGT Printability Tester

Substrate	**Ink**	**0.6 μm**	**1.8 μm**	**3.0 μm**	**4.2 μm**	**5.4 μm**
Paper	Low	143%	115%	90%	71%	55%
		133%	108%	95%	63%	52%
Paper	High	132%	125%	91%	72%	53%
		144%	108%	82%	61%	49%
Plastic	Low	188%	141%	103%	75%	47%
		182%	146%	95%	79%	52%
Plastic	High	172%	131%	102%	69%	43%
		168%	130%	115%	77%	44%

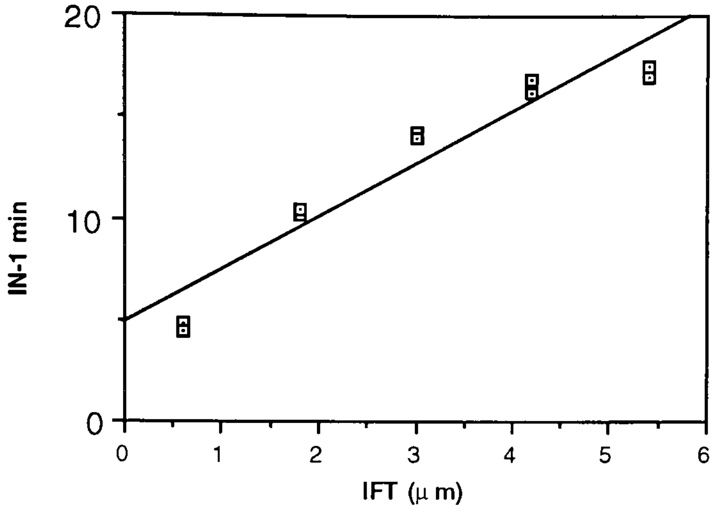
Appendix D

Graph of data, regression analysis, and R^2 of

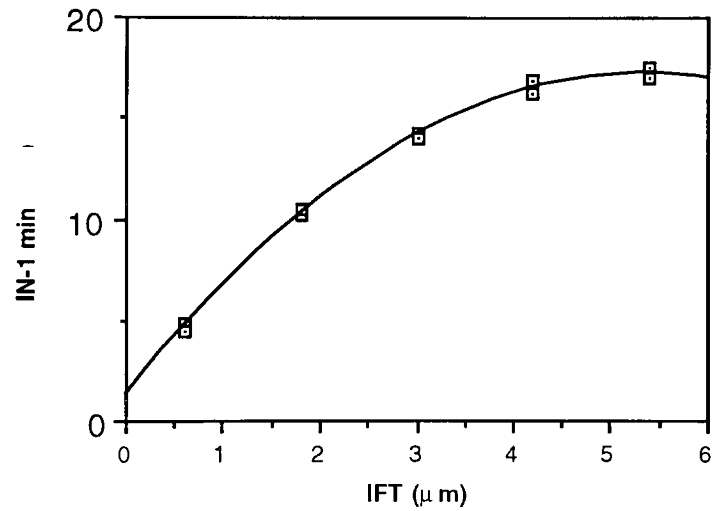
IFT vs. Inkometer response, picking velocity, and gravimetric trapping

Appendix D-1 Graph of data, regression analysis, and R^2 of the high tack ink's Inkometer response (1') vs. IFT

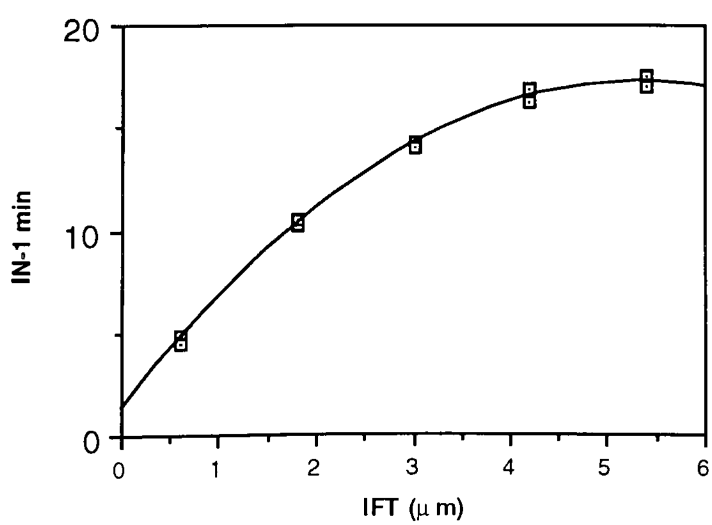
y = 4.7775 + 2.6042x   R^2 = 0.913



y = 1.3623 + 5.9524x   0.55804x^2   R^2 = 0.998

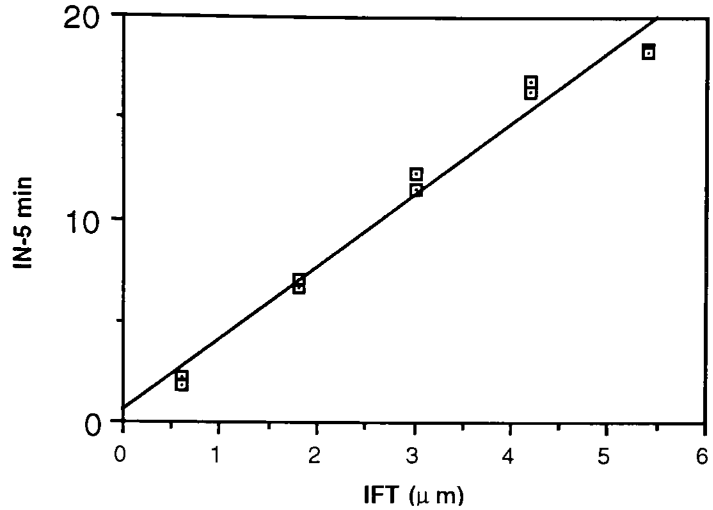


y = 1.2139 + 6.2189x   0.66654x^2 + 1.2056e-2x^3   R^2 = 0.998

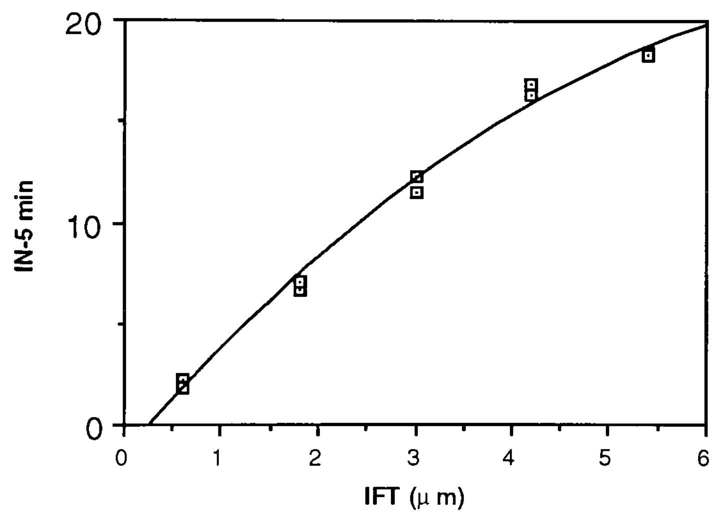


Appendix D-2 Graph of data, regression analysis, and R^2 of the high tack ink's Inkometer response (5') vs. IFT

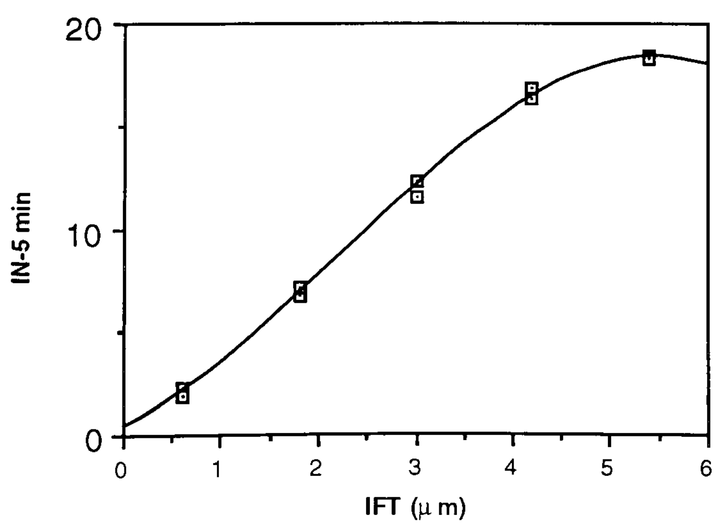
y = 0.53000 + 3.5333x   R^2 = 0.977



y = 1.4432 + 5.4679x 0.32242x^2   R^2 = 0.993

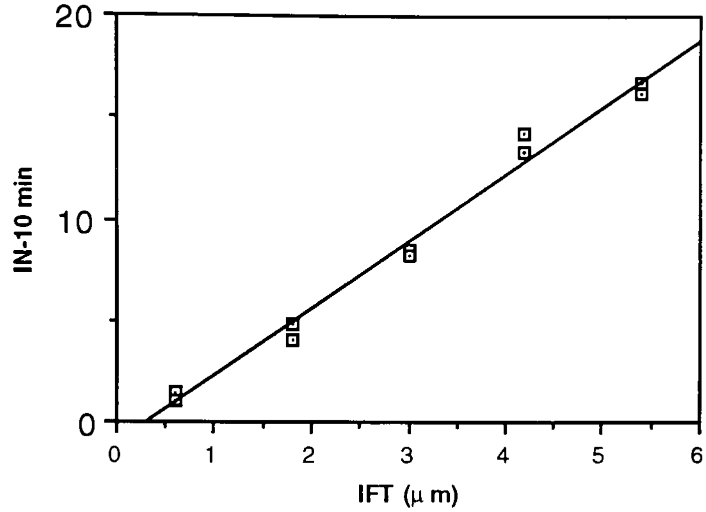


y = 0.36772 + 2.2166x + 1.0014x^2 0.14709x^3   R^2 = 0.998

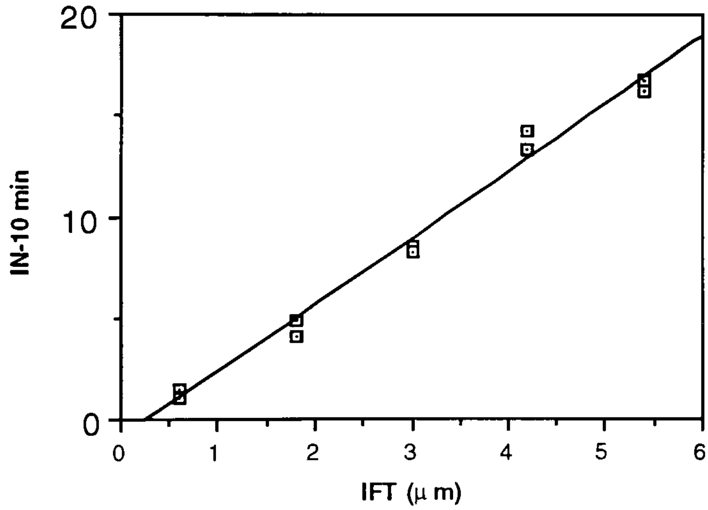


Appendix D-3 Graph of data, regression analysis, and R^2 of the high tack ink's Inkometer response (10') vs. IFT

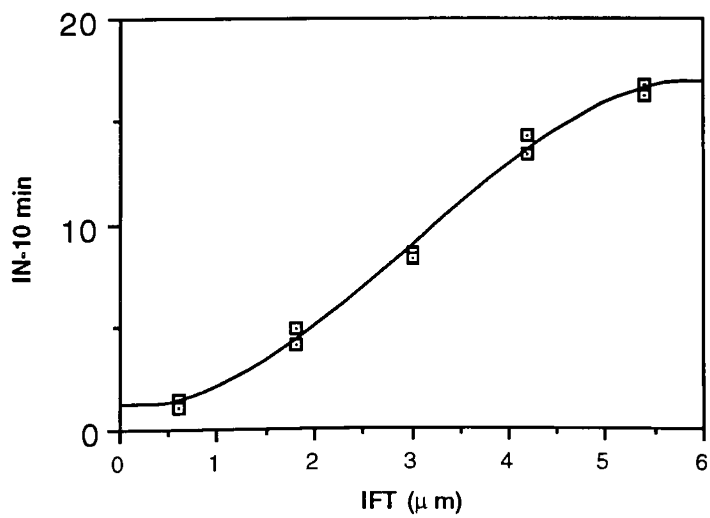
y = - 1.0300 + 3.3000x R^2 = 0.988



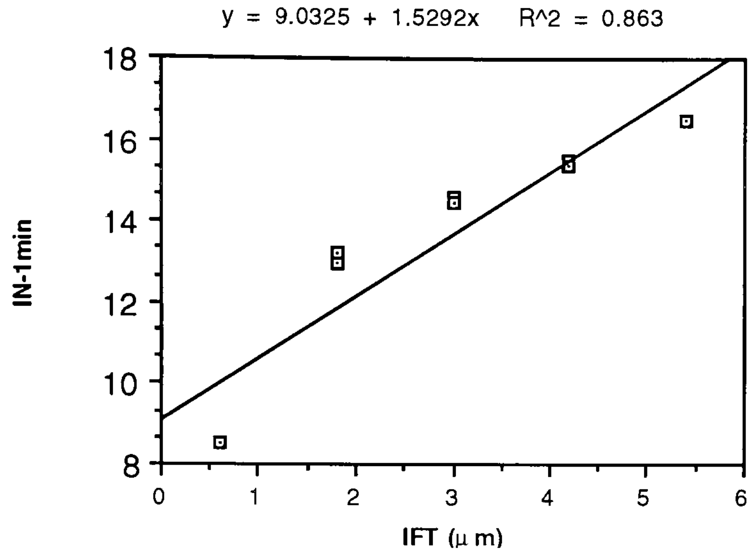
y = 0.87821 + 3.1512x + 2.4802e-2x^2 R^2 = 0.988

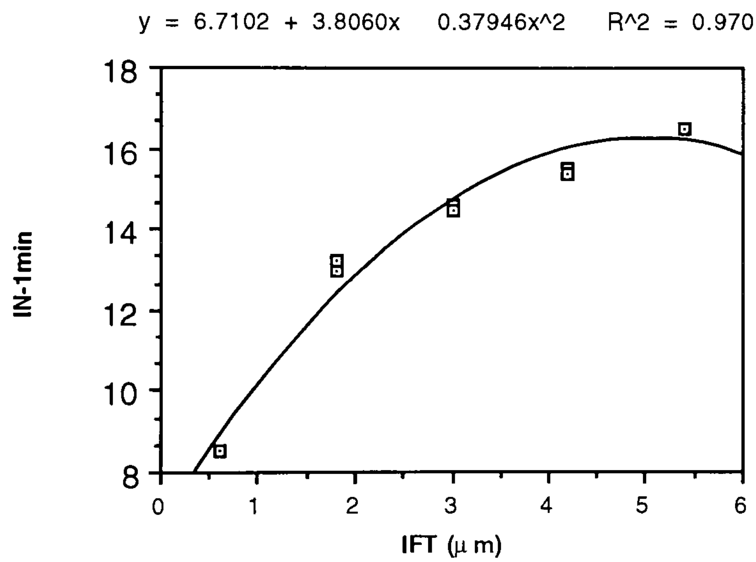


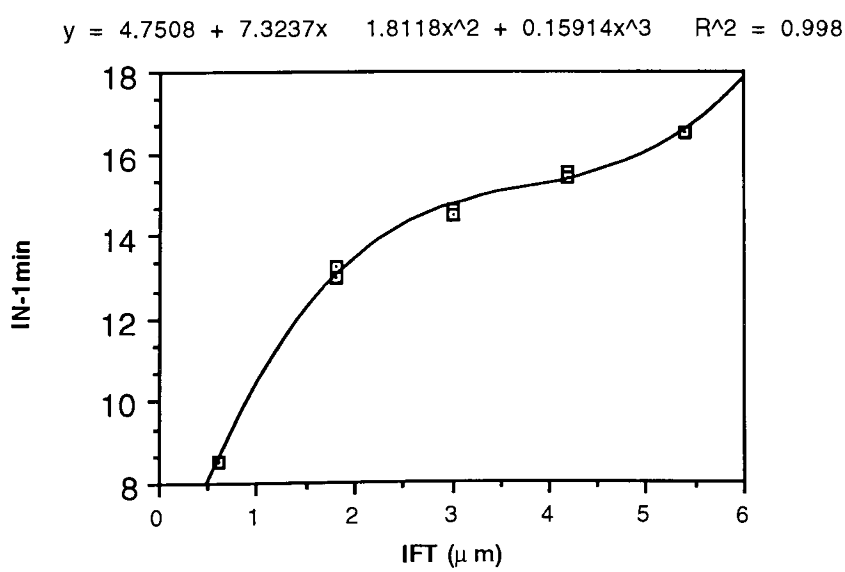
y = 1.1702 0.52641x + 1.5222x^2 0.16638x^3 R^2 = 0.995



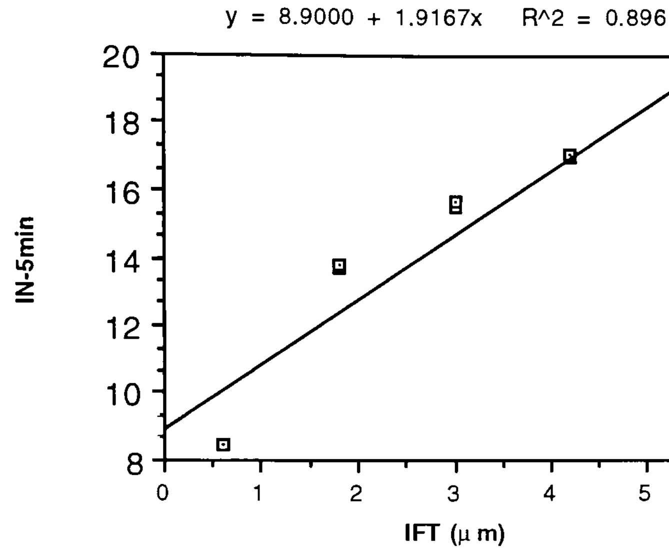
Appendix D-4 Graph of data, regression analysis, and R^2 of the low tack ink's Inkometer response (1') vs. IFT

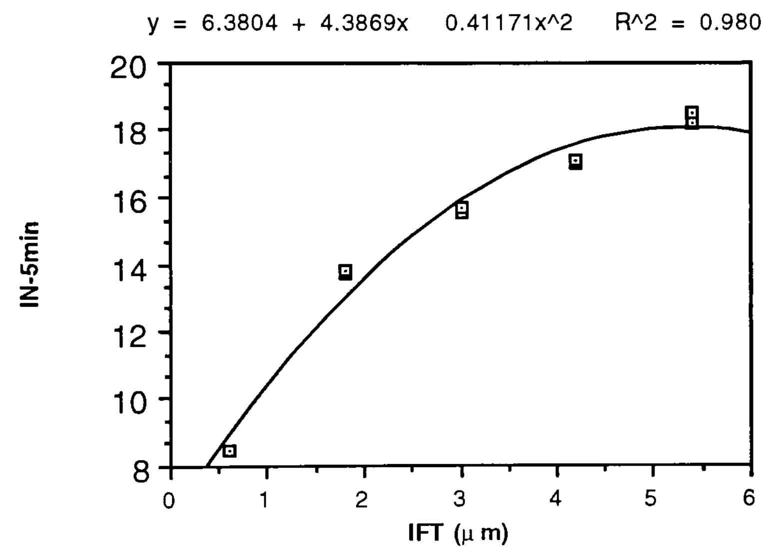


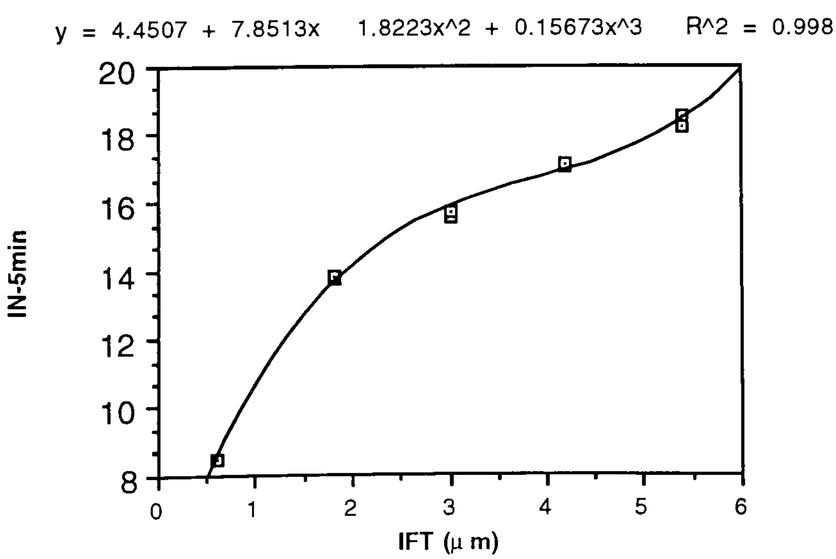




Appendix D-5 Graph of data, regression analysis, and R^2 of the low tack ink's Inkometer response (5') vs. IFT

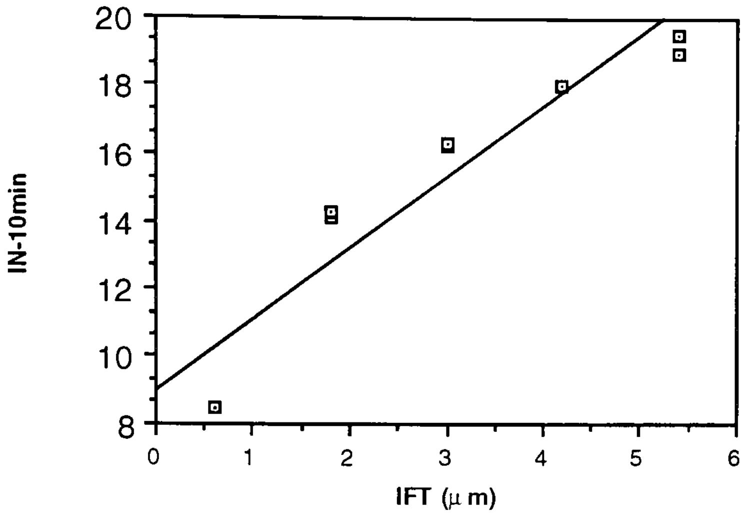




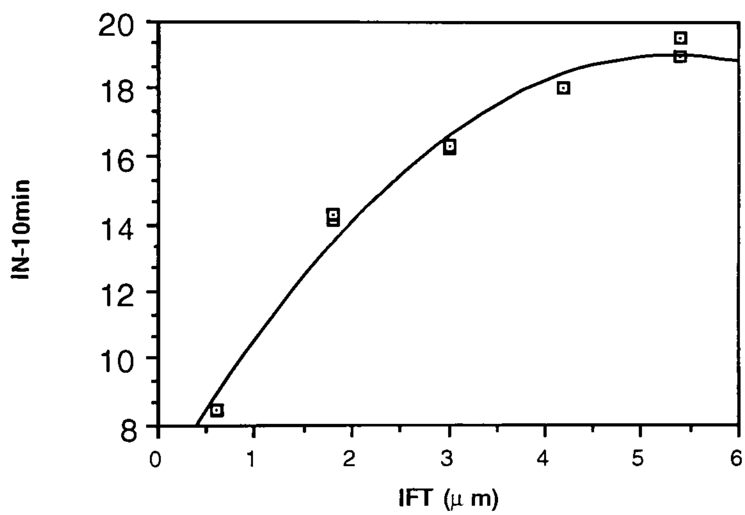


Appendix D-6 Graph of data, regression analysis, and R^2 of the low tack ink's Inkometer response (10') vs. IFT

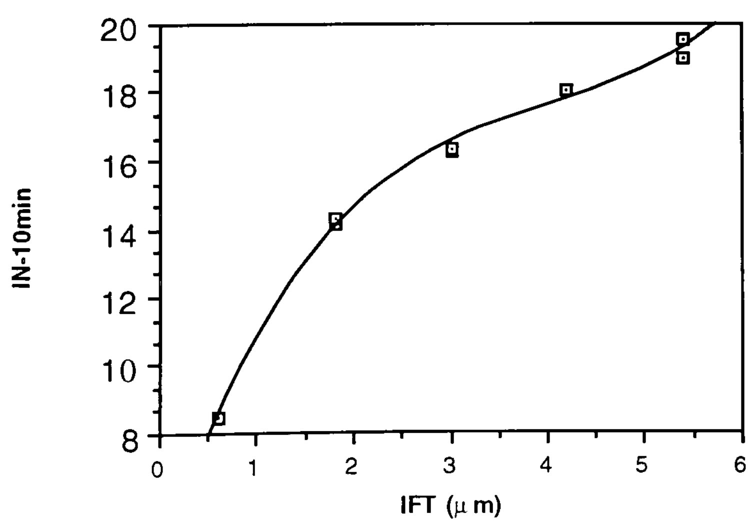
y = 8.9150 + 2.1083x   R^2 = 0.898



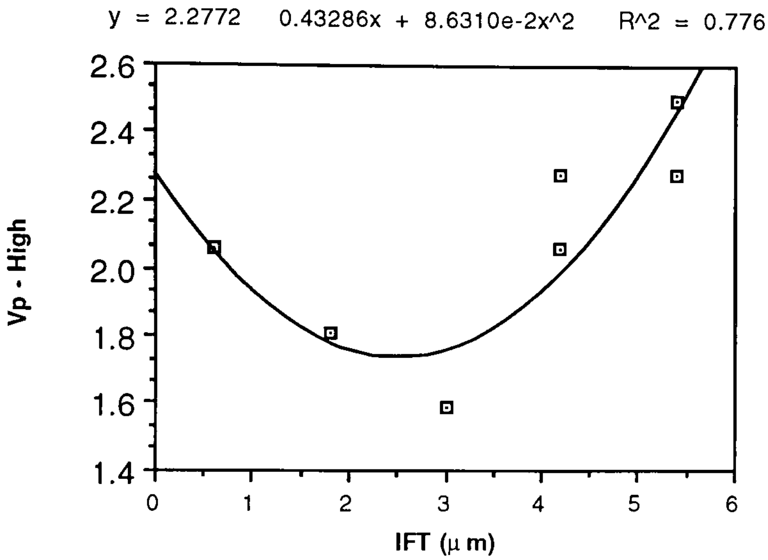
y = 6.1221 + 4.8464x   0.45635x^2   R^2 = 0.983

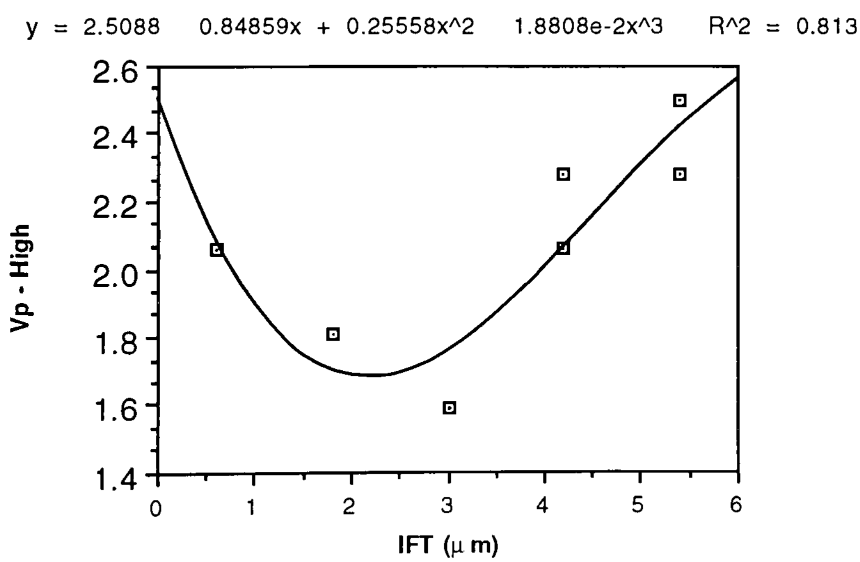


y = 4.2518 + 8.2042x   1.8235x^2 + 0.15191x^3   R^2 = 0.996

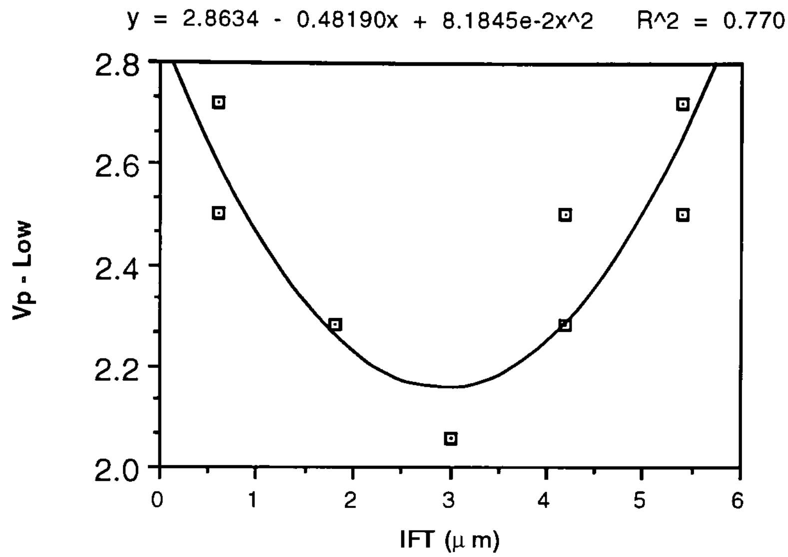


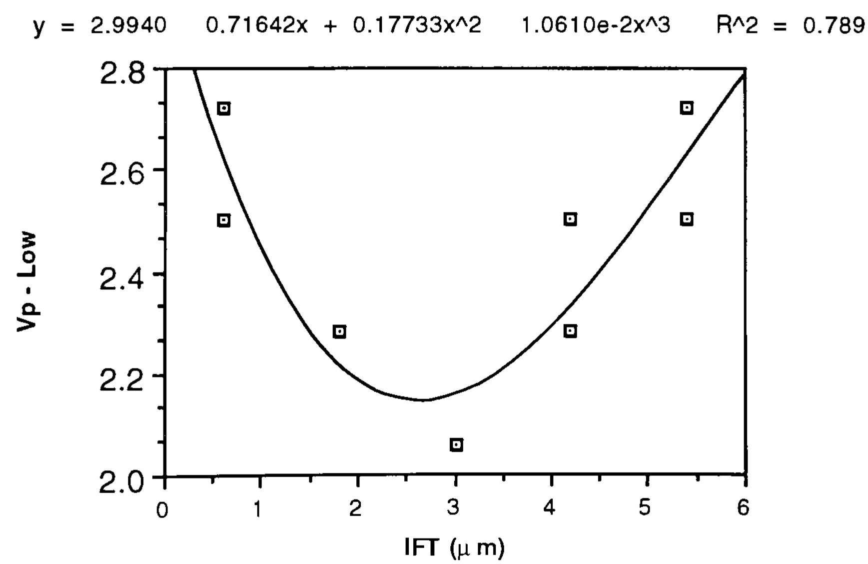
Appendix D-7 Graph of data, regression analysis, and R^2 of the high tack ink's picking velocity vs. IFT





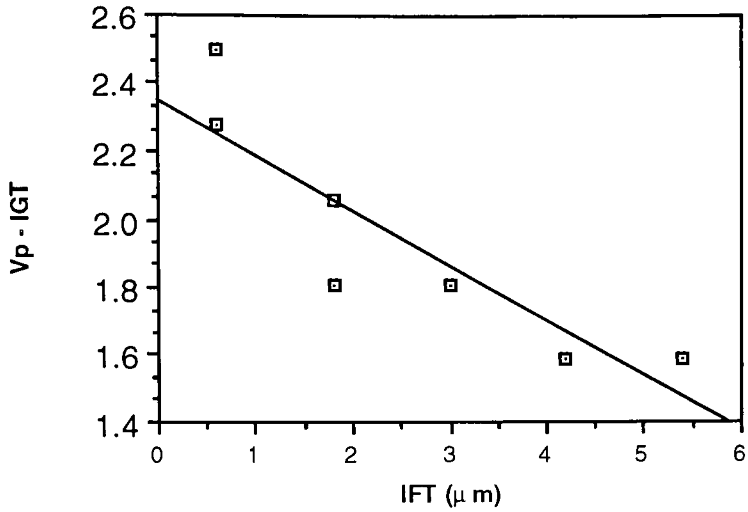
Appendix D-8 Graph of data, regression analysis, and R^2 of the low tack ink's picking velocity vs. IFT



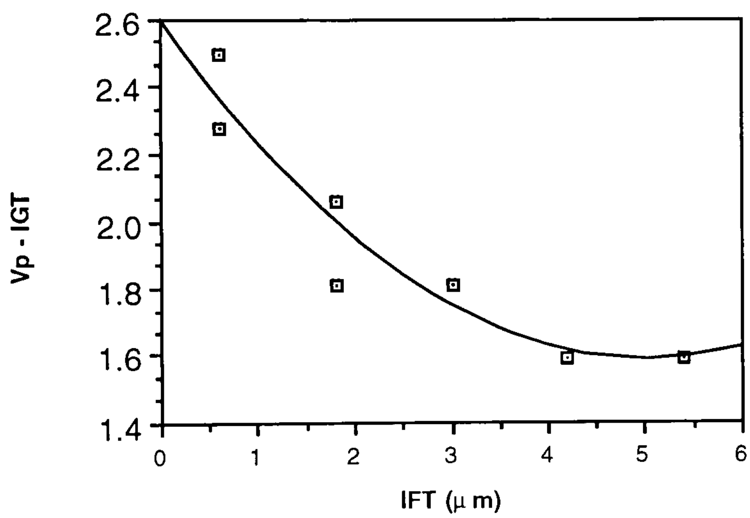


Appendix D-9 Graph of data, regression analysis, and R^2 of the IGT oil's picking velocity vs. IFT

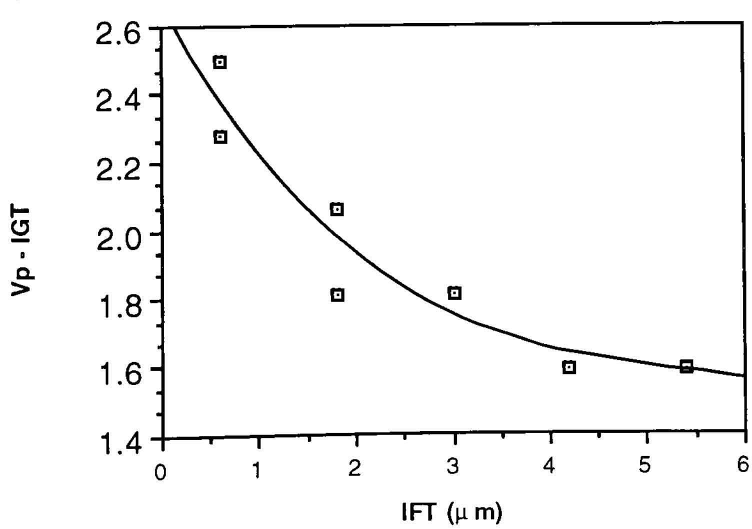
y = 2.3492 - 0.16208x R^2 = 0.818



y = 2.5967 0.40464x + 4.0427e-2x^2 R^2 = 0.921

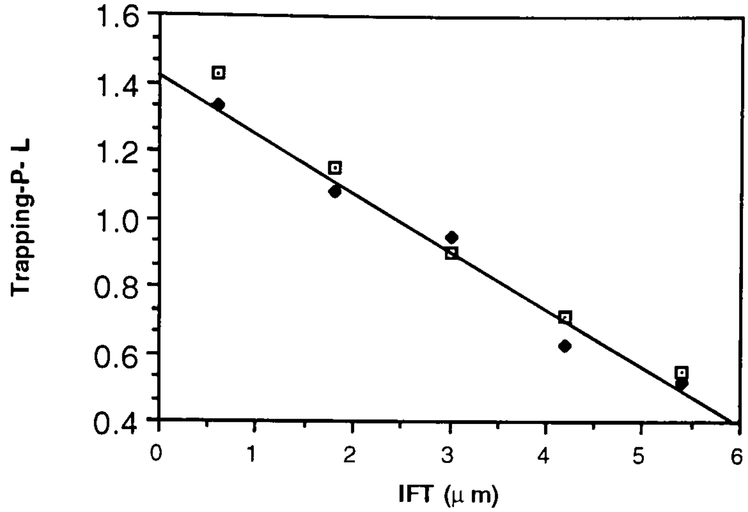


y = 2.6620 0.52190x + 8.8170e-2x^2 5.3048e-3x^3 R^2 = 0.923

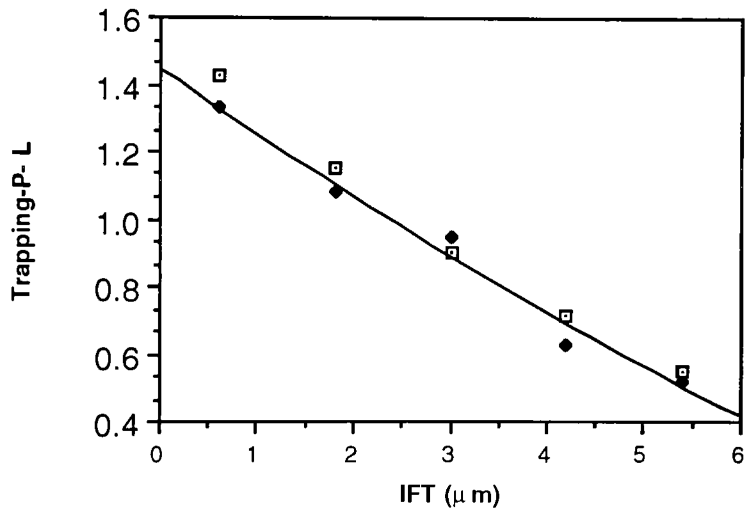


Appendix D-10 Graph of data, regression analysis, and R^2 of the low tack ink and paper's gravimetric trapping vs. IFT

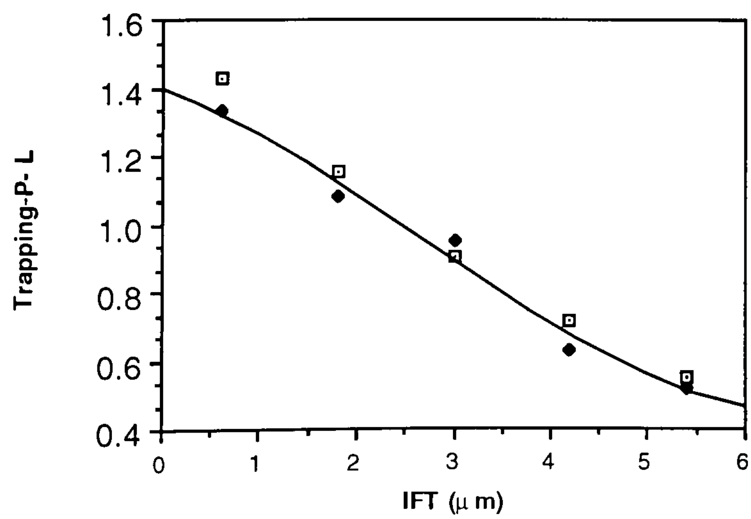
y = 1.4195 0.17250x R^2 = 0.980



y = 1.4468 0.19929x + 4.4643e-3x^2 R^2 = 0.982

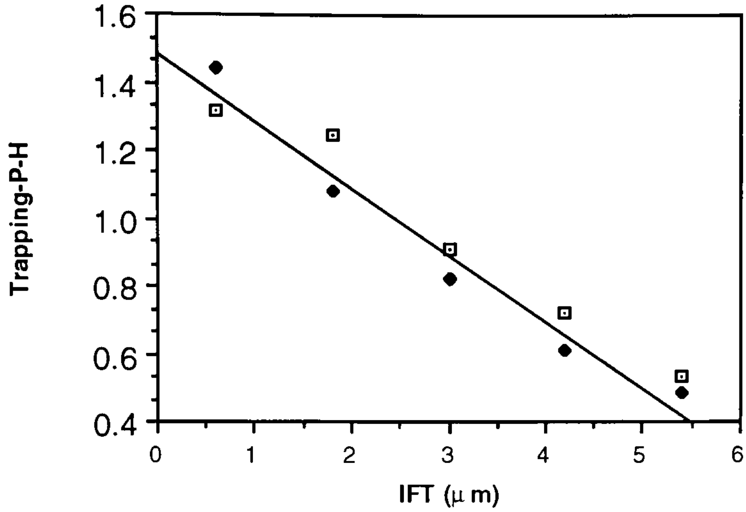


y = 1.3934 0.10335x 3.4598e-2x^2 + 4.3403e-3x^3 R^2 = 0.984

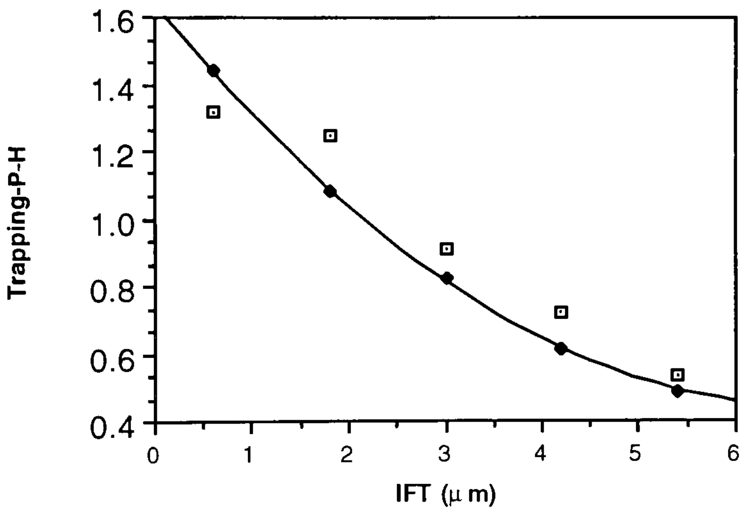


Appendix D-11 Graph of data, regression analysis, and R^2 of the high tack ink and paper's gravimetric trapping vs. IFT

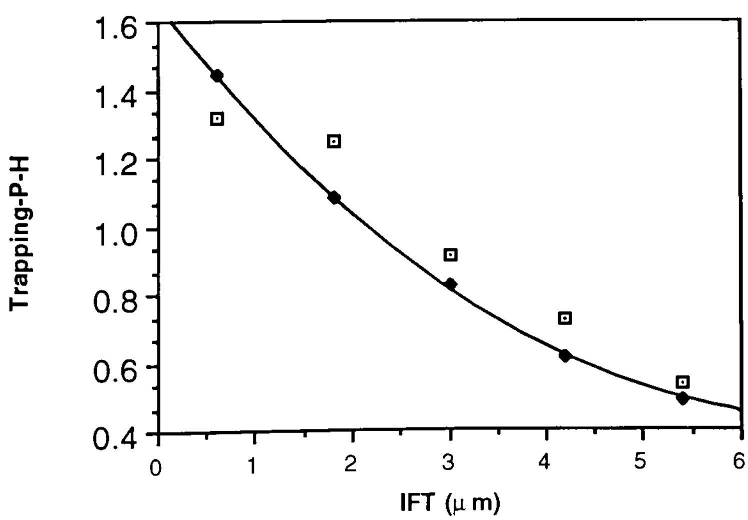
y = 1.4805 0.19750x R^2 = 0.965



y = 1.6414 0.35524x + 2.6290e-2x^2 R^2 = 1.000

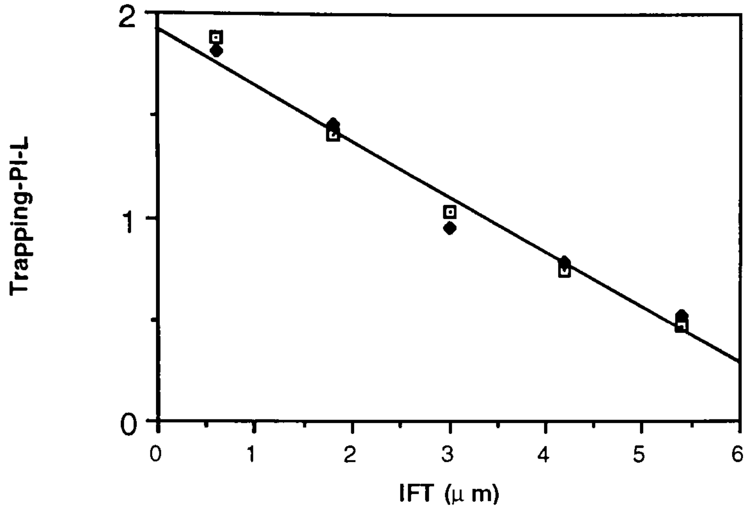


y = 1.6473 0.36590x + 3.0630e-2x^2 4.8225e-4x^3 R^2 = 1.000

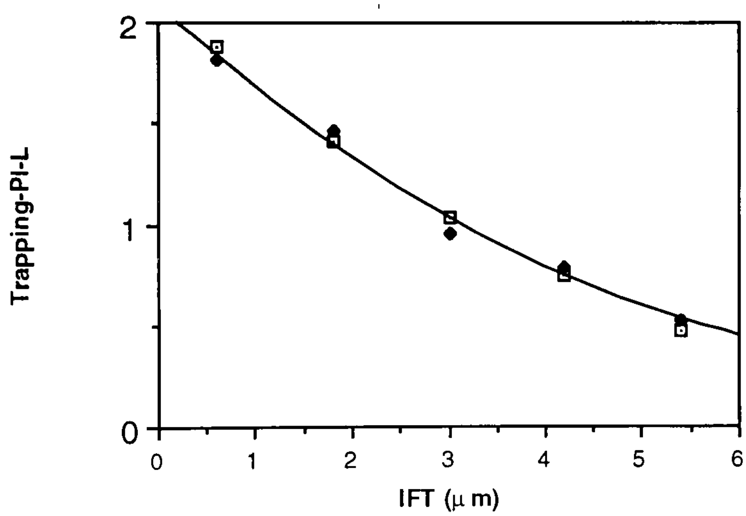


Appendix D-12 Graph of data, regression analysis, and R^2 of the low tack ink and plastic film's gravimetric trapping vs. IFT

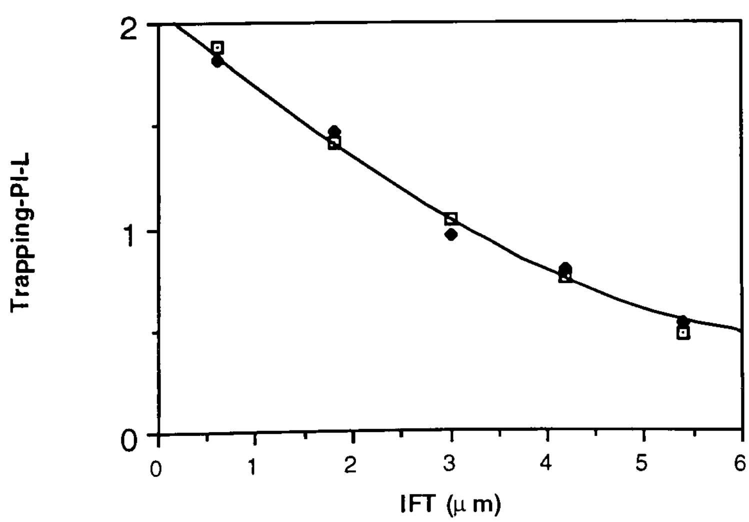
y = 1.9255 - 0.27250x   R^2 = 0.970



y = 2.0864   0.43024x + 2.6290e-2x^2   R^2 = 0.988

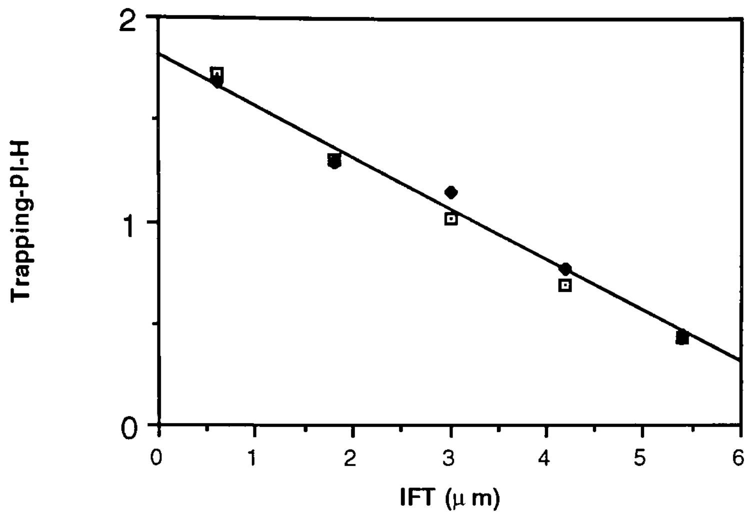


y = 2.0626   0.38760x + 8.9286e-3x^2 + 1.9290e-3x^3   R^2 = 0.988

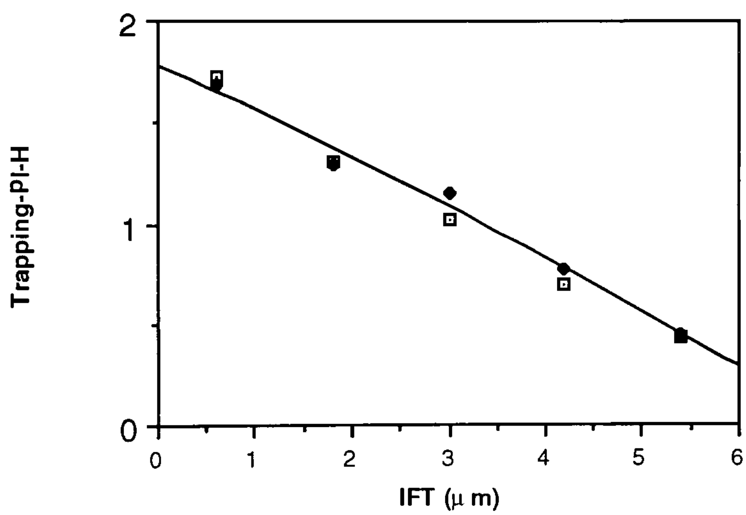


Appendix D-13 Graph of data, regression analysis, and R^2 of the high tack ink and plastic film's gravimetric trapping vs. IFT

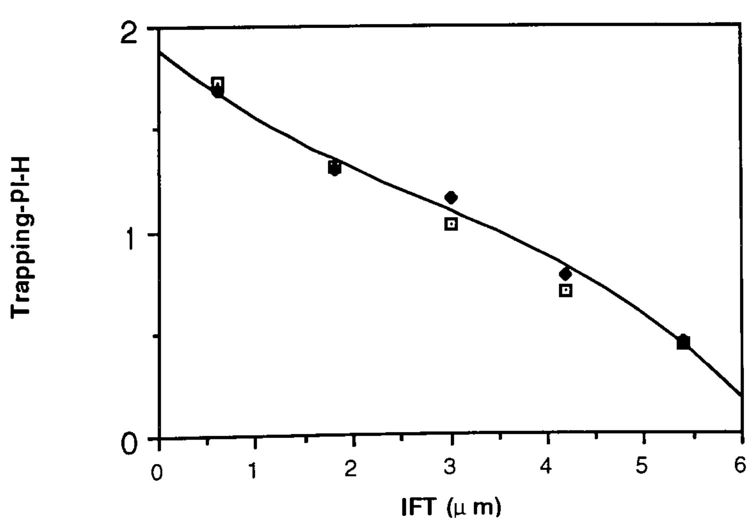
y = 1.8205 0.25083x R^2 = 0.987



y = 1.7810 0.21214x 6.4484e-3x^2 R^2 = 0.988



y = 1.8879 0.40402x + 7.1677e-2x^2 8.6806e-3x^3 R^2 = 0.991

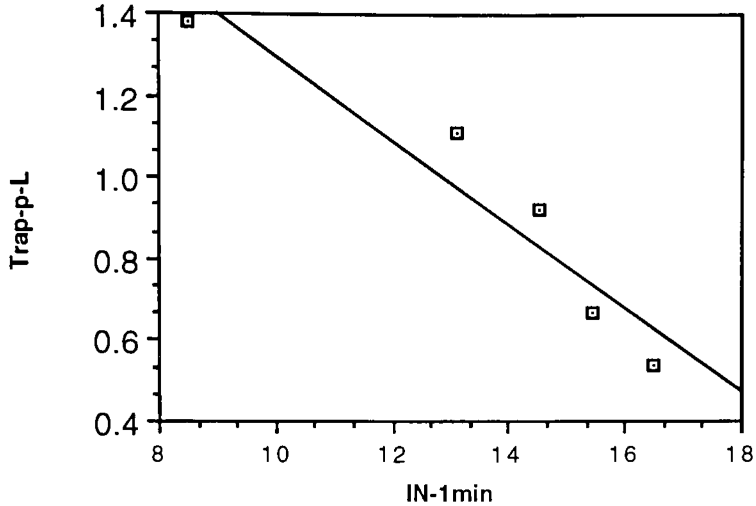


Appendix E

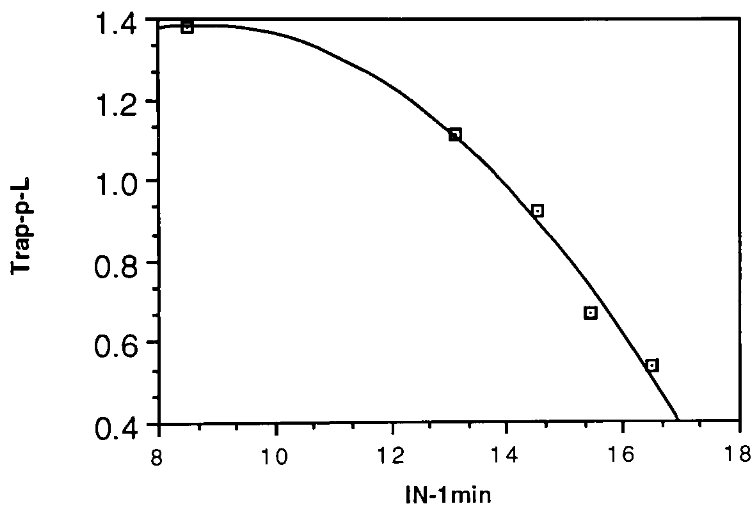
Graph of data, regression analysis, and R^2 of Inkometer response vs. gravimetric trapping

Appendix E-1 Graph of data, regression analysis, and R^2 of the low tack ink and paper's gravimetric trapping vs. Inkometer response-1 min

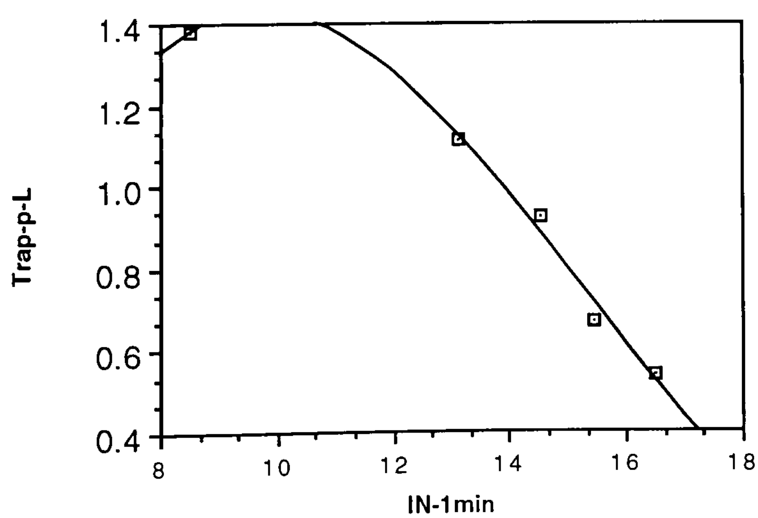
y = 2.3285 - 0.10305x   R^2 = 0.900



y = 0.24719 + 0.25847x   1.4705e-2x^2   R^2 = 0.988

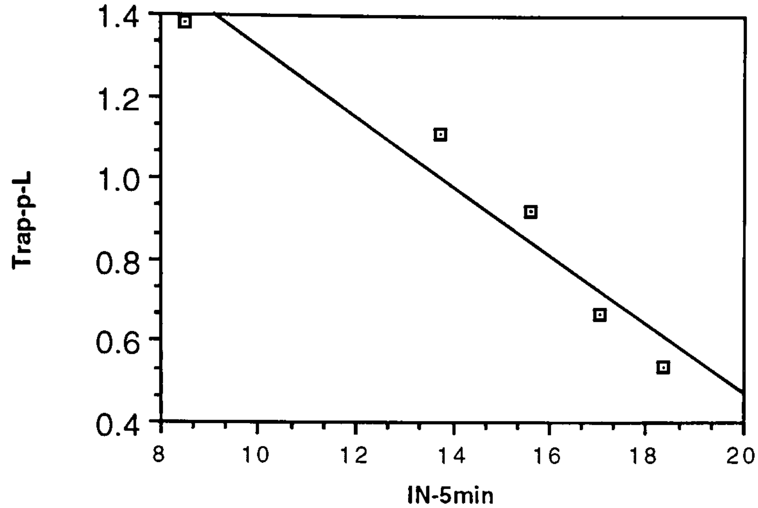


y = 3.4154 + 1.1804x   8.8901e-2x^2 + 1.9288e-3x^3   R^2 = 0.991

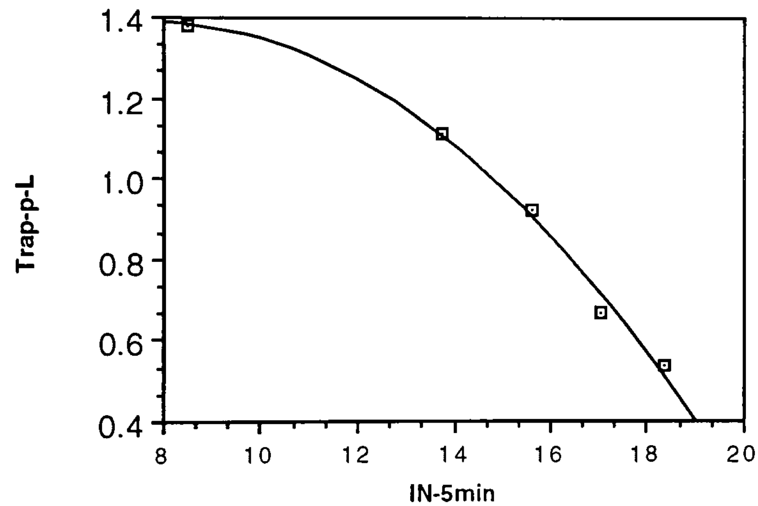


Appendix E-2 Graph of data, regression analysis, and R^2 of the low tack ink and paper's gravimetric trapping vs. Inkometer response-5 min

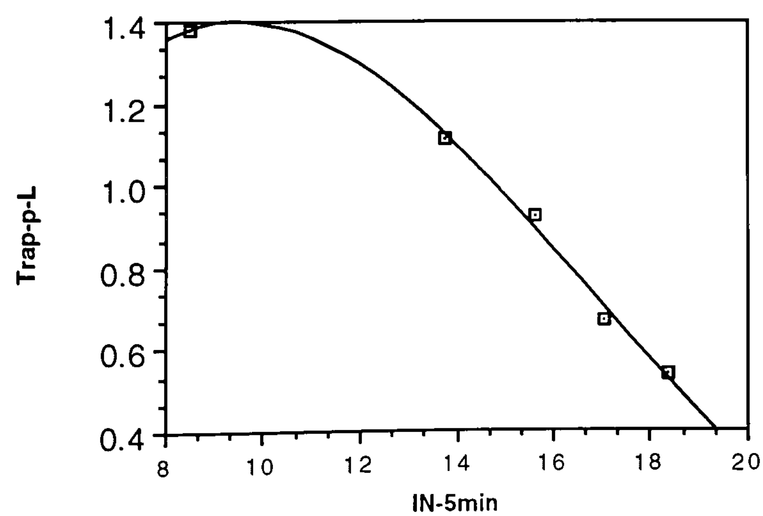
y = 2.1729 8.5178e-2x R^2 = 0.930



y = 0.90799 + 0.12251x 7.8516e-3x^2 R^2 = 0.994

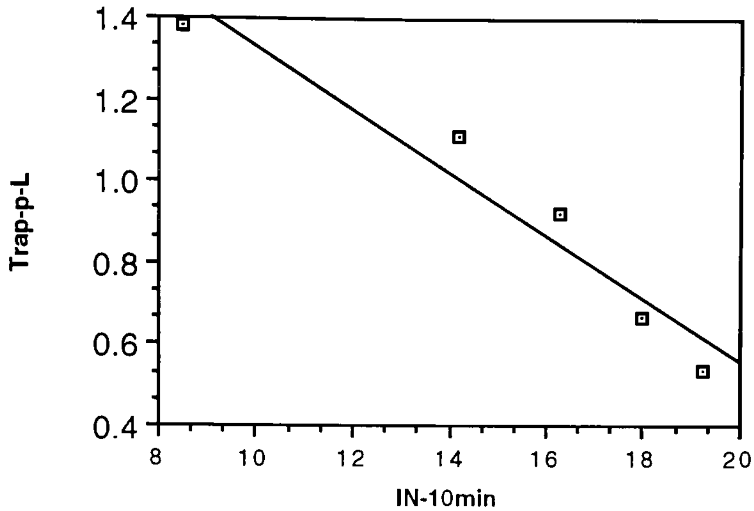


y = - 1.0325 + 0.58989x 4.3344e-2x^2 + 8.6236e-4x^3 R^2 = 0.996

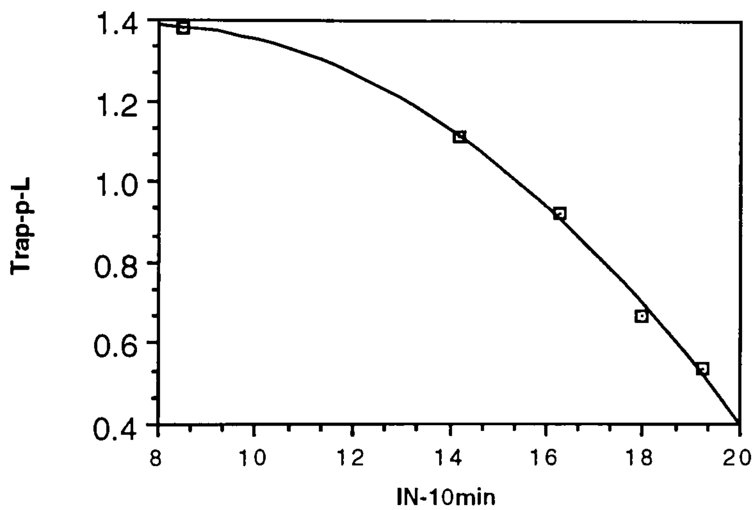


Appendix E-3 Graph of data, regression analysis, and R^2 of the low tack ink and paper's gravimetric trapping vs. Inkometer response-10 min

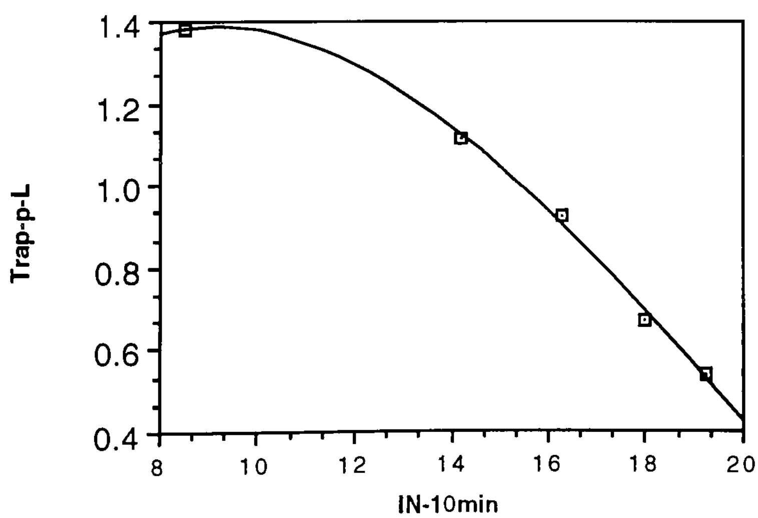
y = 2.1086 7.7667e-2x R^2 = 0.934



y = 0.98802 + 0.10200x 6.5620e-3x^2 R^2 = 0.997

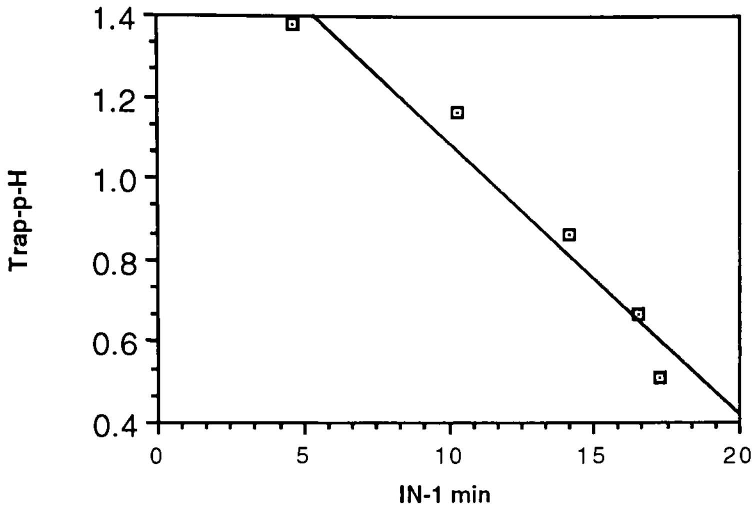


y = 0.13061 + 0.30434x 2.1504e-2x^2 + 3.5135e-4x^3 R^2 = 0.998

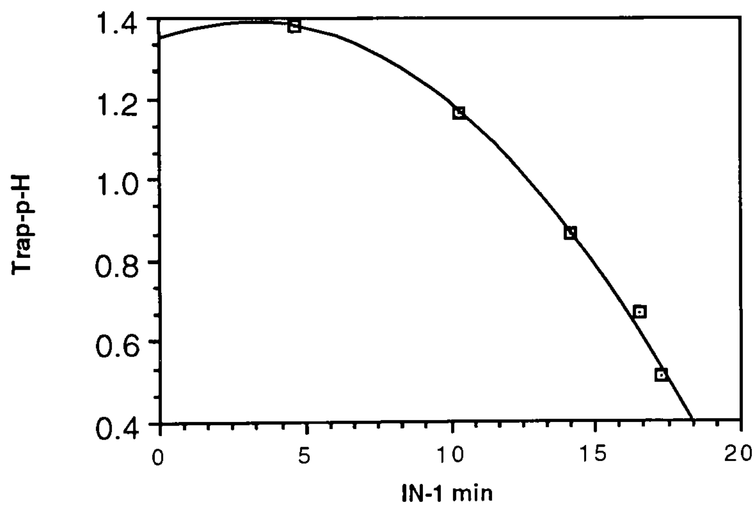


Appendix E-4 Graph of data, regression analysis, and R^2 of the high tack ink and paper's gravimetric trapping vs. Inkometer response-1 min

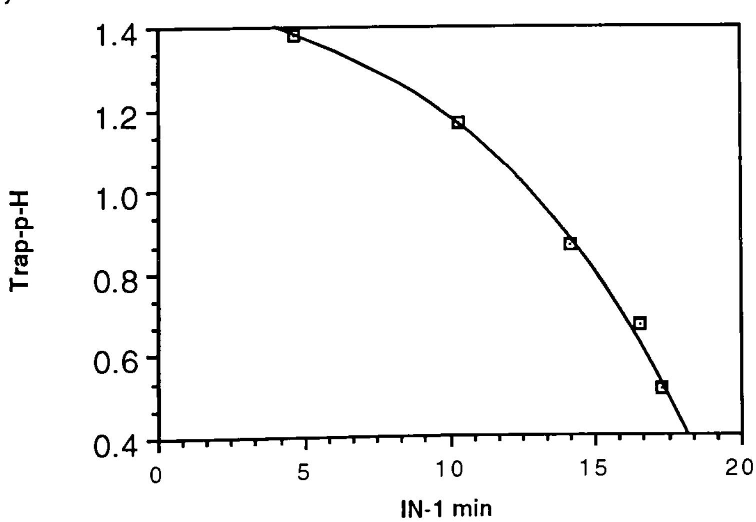
y = 1.7632 6.7209e-2x R^2 = 0.949



y = 1.3447 + 2.7435e-2x 4.2989e-3x^2 R^2 = 0.995

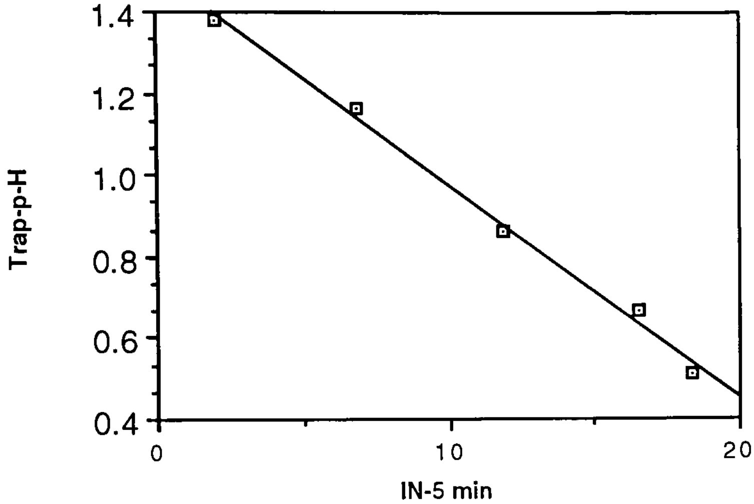


y = 1.5080 3.0117e-2x + 1.4498e-3x^2 1.7286e-4x^3 R^2 = 0.996

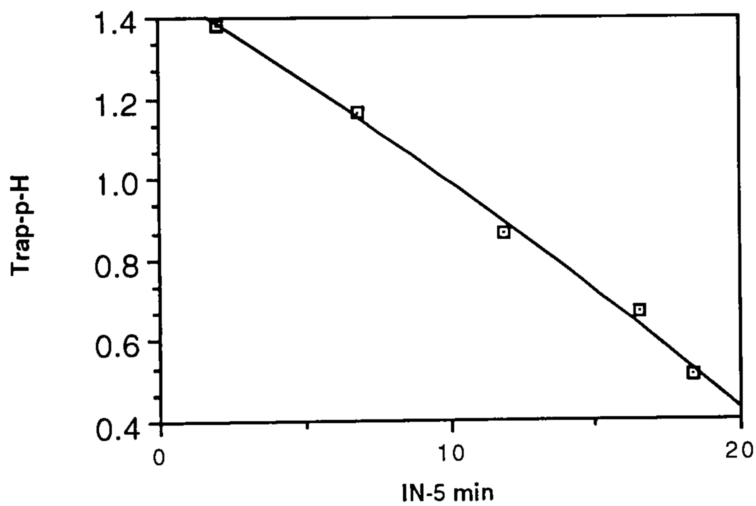


Appendix E-5 Graph of data, regression analysis, and R^2 of the high tack ink and paper's gravimetric trapping vs. Inkometer response-5 min

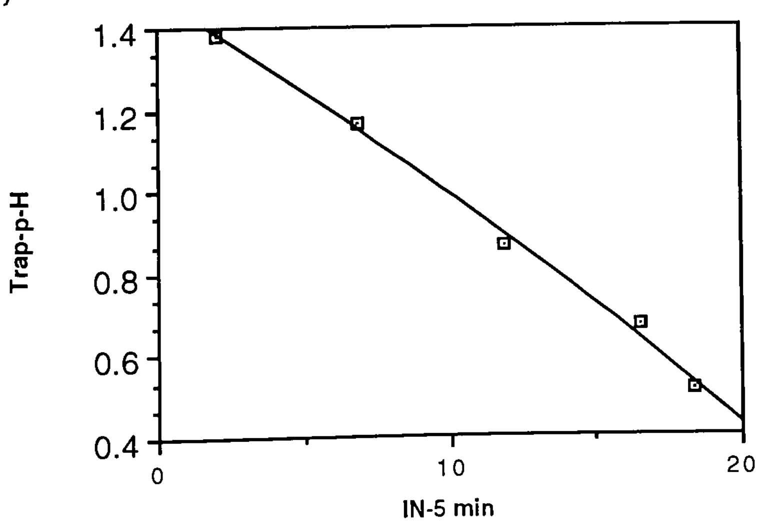
y = 1.5004   5.2418e-2x   R^2 = 0.995



y = 1.4734   4.4328e-2x   3.9256e-4x^2   R^2 = 0.996

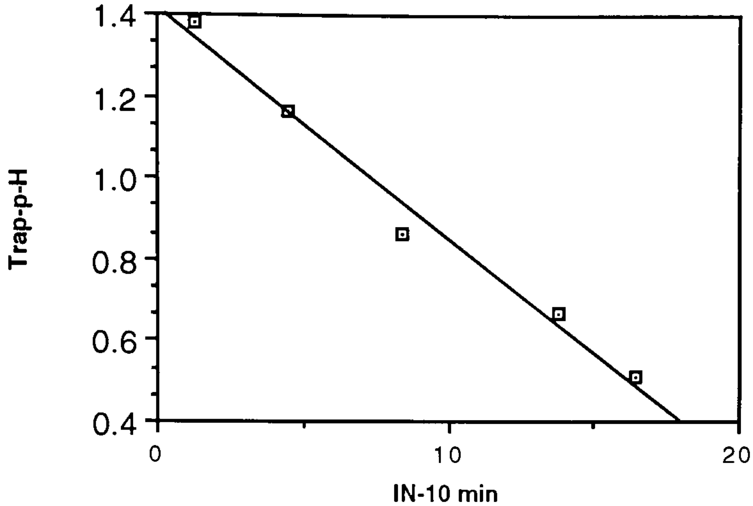


y = 1.4746   4.4972e-2x   3.1380e-4x^2   2.6073e-6x^3   R^2 = 0.996

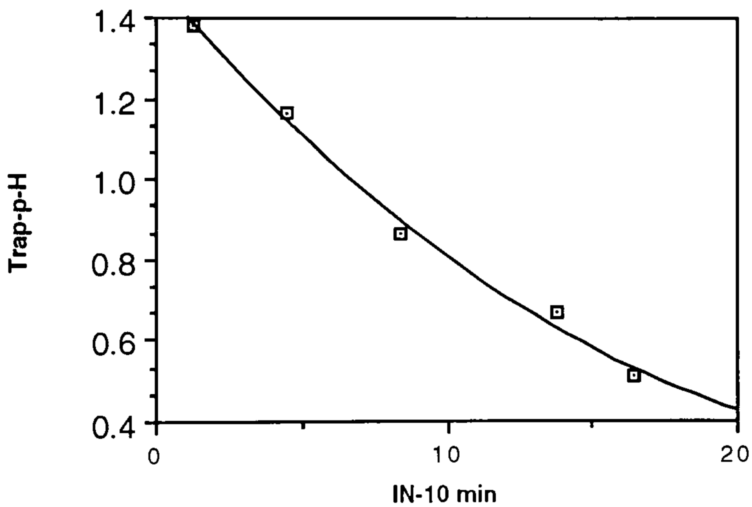


Appendix E-6 Graph of data, regression analysis, and R^2 of the high tack ink and paper's gravimetric trapping vs. Inkometer response-10 min

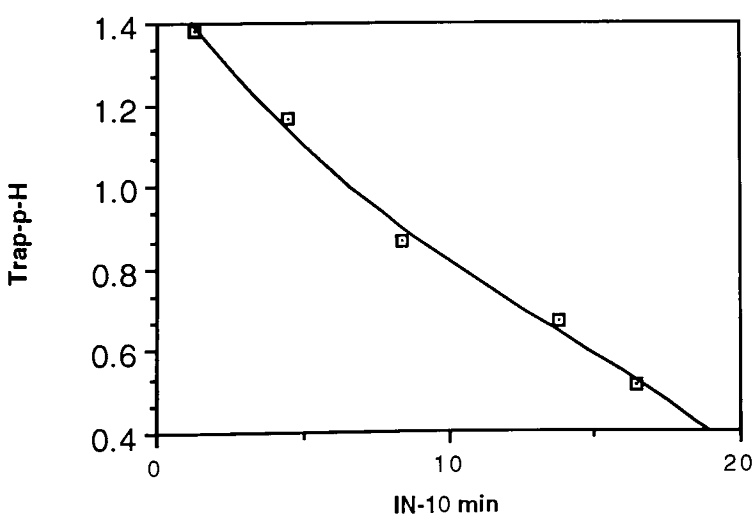
y = 1.4151   5.6157e-2x   R^2 = 0.983



y = 1.4878   8.2900e-2x + 1.4908e-3x^2   R^2 = 0.994

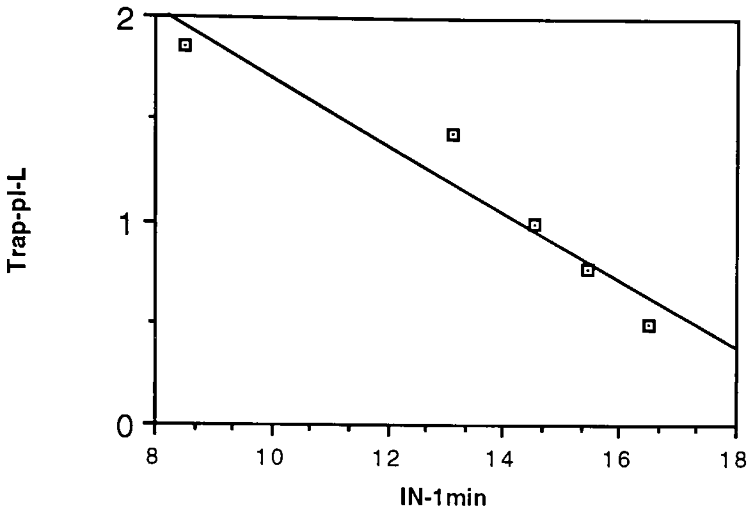


y = 1.5130   0.10042x + 4.0397e-3x^2   9.7611e-5x^3   R^2 = 0.995

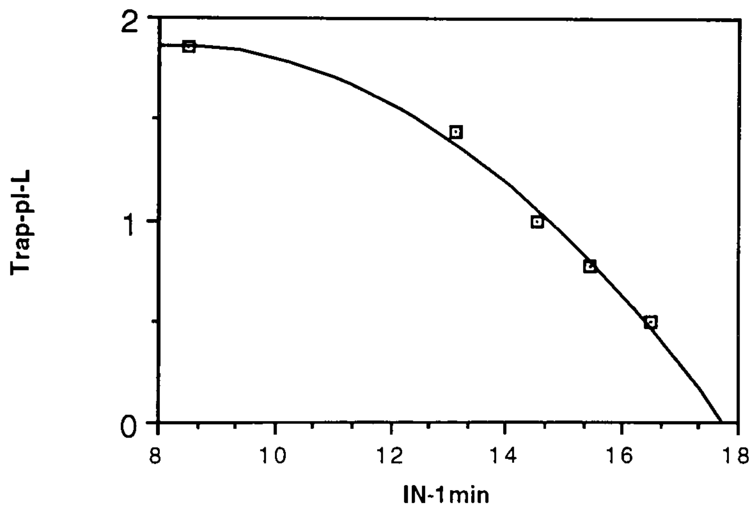


Appendix E-7 Graph of data, regression analysis, and R^2 of the low tack ink and plastic film's gravimetric trapping vs. Inkometer response-1 min

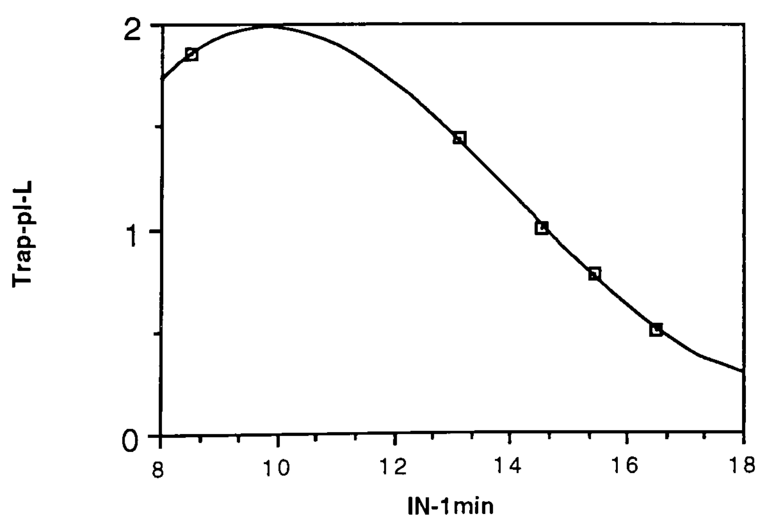
y = 3.3654 - 0.16574x R^2 = 0.922



y = 0.41536 + 0.34666x 2.0842e-2x^2 R^2 = 0.993

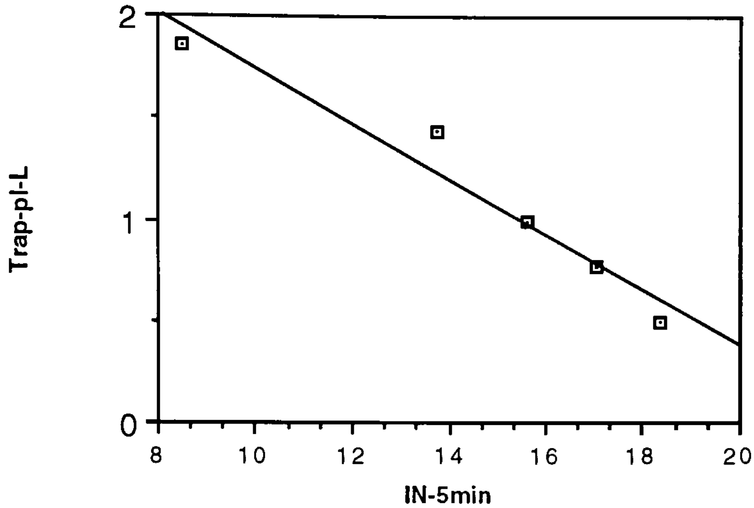


y = 9.6139 + 2.8712x 0.22401x^2 + 5.2817e-3x^3 R^2 = 0.999

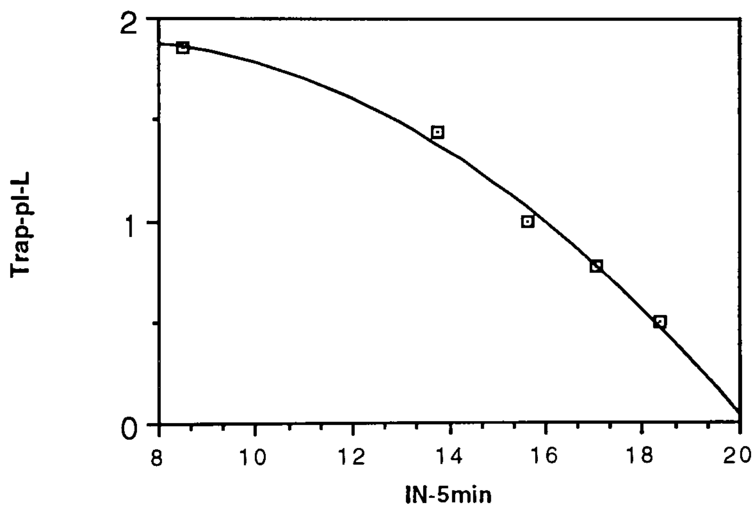


Appendix E-8 Graph of data, regression analysis, and R^2 of the low tack ink and plastic film's gravimetric trapping vs. Inkometer response-5 min

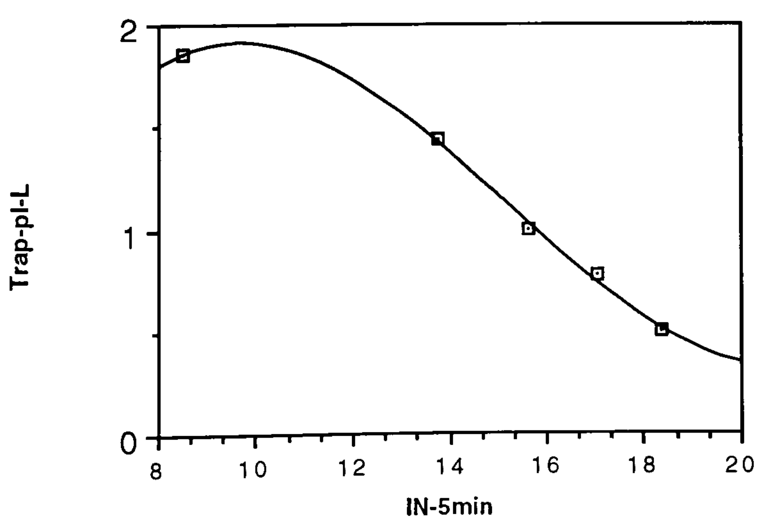
y = 3.1071   0.13646x   R^2 = 0.946



y = 1.4088 + 0.14239x   1.0542e-2x^2   R^2 = 0.991

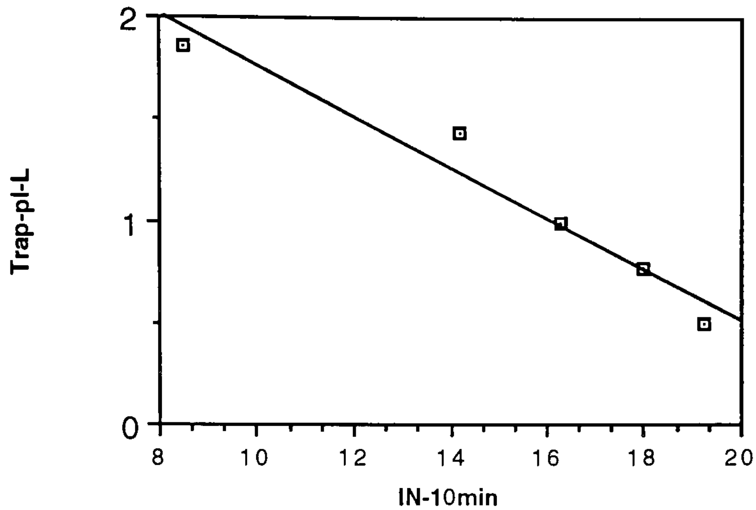


y =   3.8462 + 1.4081x   0.10666x^2 + 2.3353e-3x^3   R^2 = 0.997

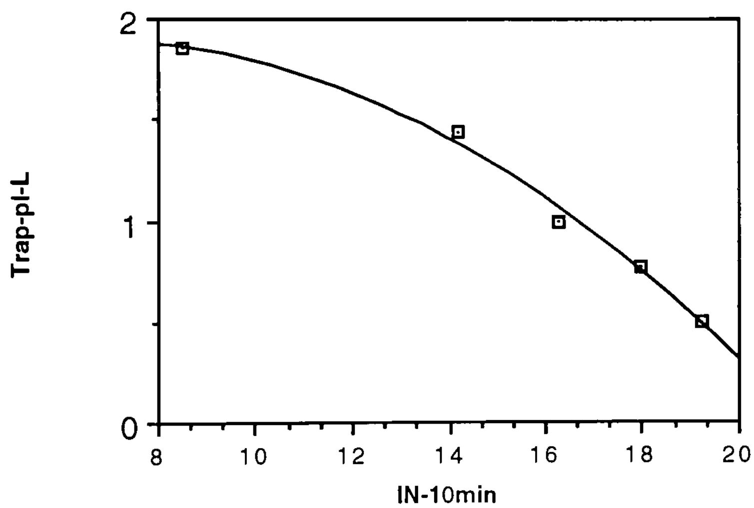


Appendix E-9 Graph of data, regression analysis, and R^2 of the low tack ink and plastic film's gravimetric trapping vs. Inkometer response-10 min

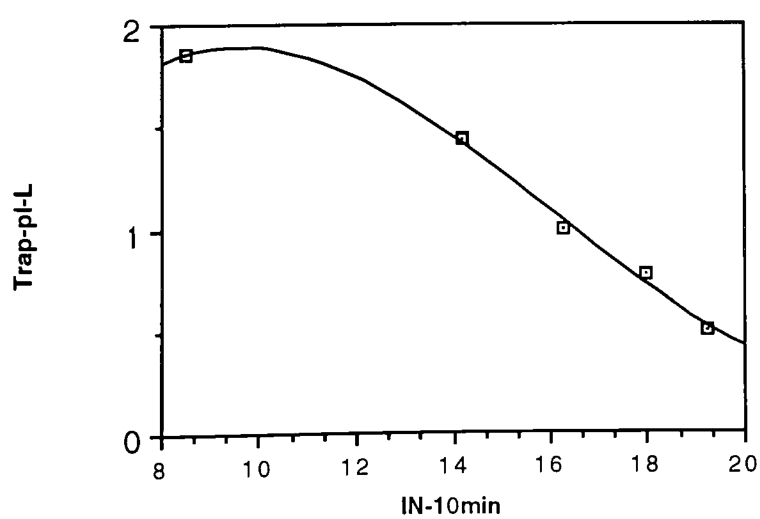
y = 3.0019 - 0.12427x   R^2 = 0.947



y = 1.5212 + 0.11313x   8.6702e-3x^2   R^2 = 0.991

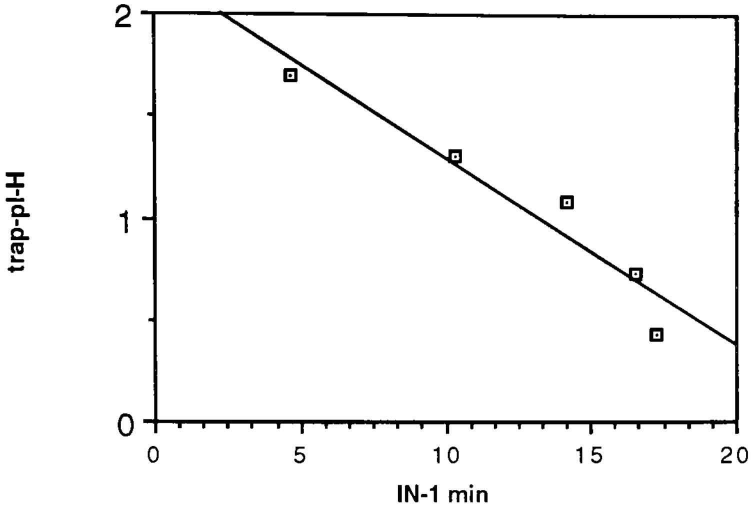


y = 2.0445 + 0.95458x   7.0808e-2x^2 + 1.4611e-3x^3   R^2 = 0.995

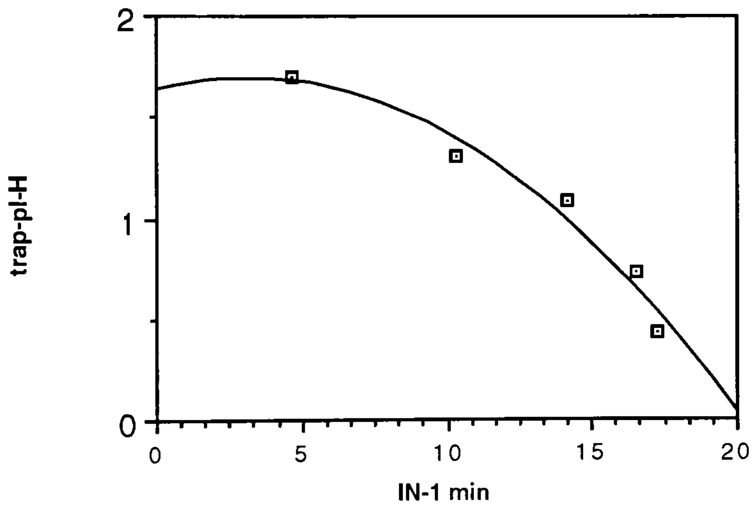


Appendix E-10 Graph of data, regression analysis, and R^2 of the high tack ink and plastic film's gravimetric trapping vs. Inkometer response-1 min

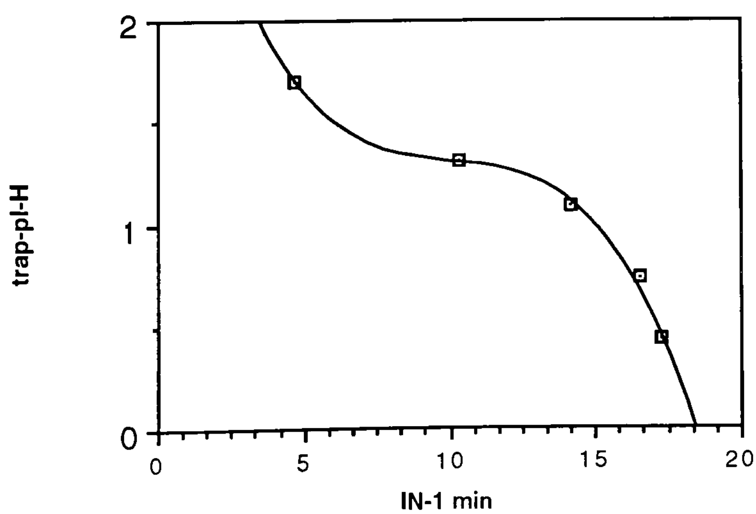
y = 2.2028 9.1486e-2x R^2 = 0.921



y = 1.6328 + 3.7451e-2x 5.8566e-3x^2 R^2 = 0.966

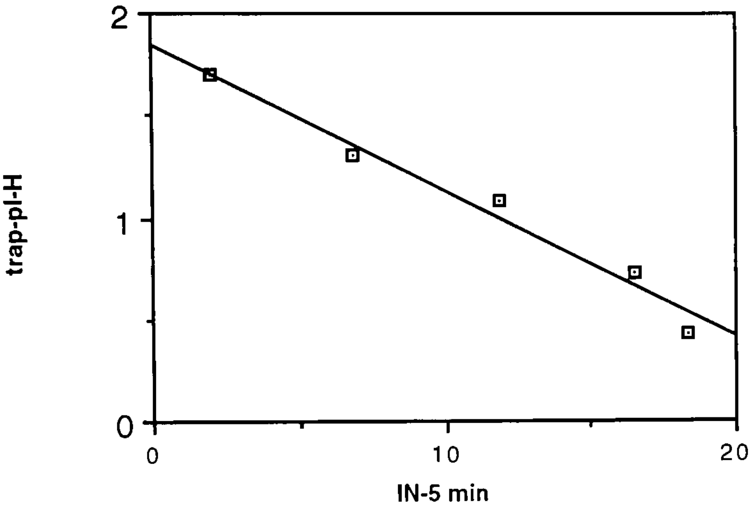


y = 3.5187 0.62721x + 6.0534e-2x^2 1.9963e-3x^3 R^2 = 0.996

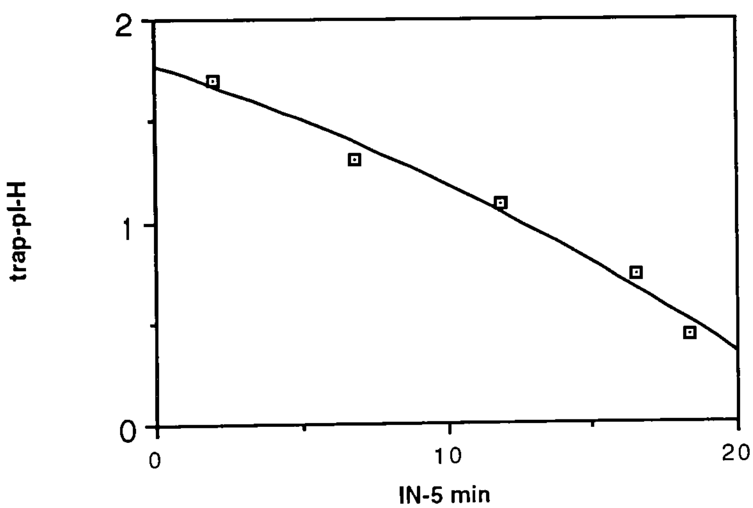


Appendix E-11 Graph of data, regression analysis, and R^2 of the high tack ink and plastic film's gravimetric trapping vs. Inkometer response-5 min

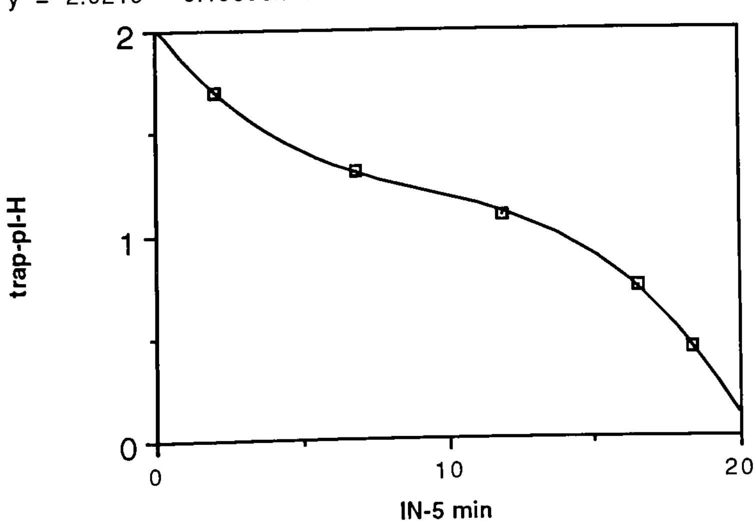
y = 1.8488 7.1684e-2x R^2 = 0.974



y = 1.7628 4.5881e-2x 1.2520e-3x^2 R^2 = 0.980

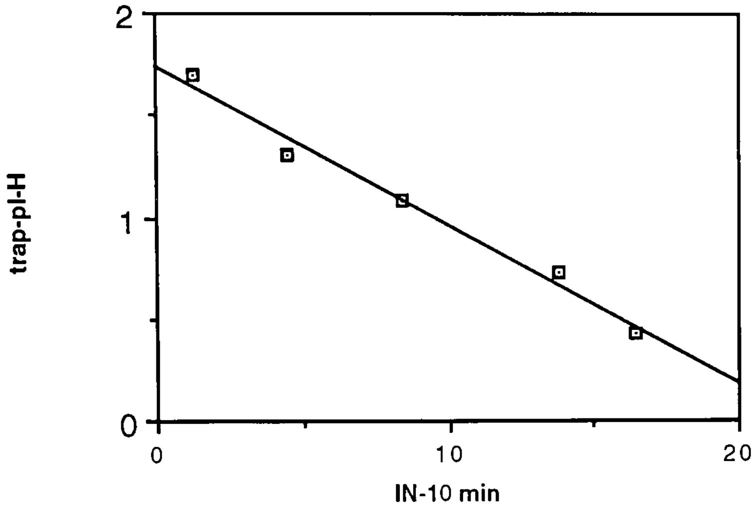


y = 2.0219 0.19090x + 1.6489e-2x^2 5.8733e-4x^3 R^2 = 1.000

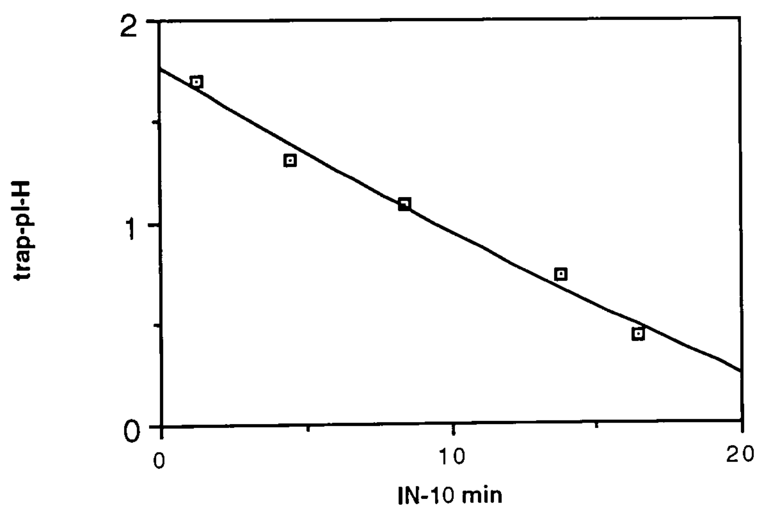


Appendix E-12 Graph of data, regression analysis, and R^2 of the high tack ink and plastic film's gravimetric trapping vs. Inkometer response-10 min

y = 1.7394 7.7604e-2x R^2 = 0.984



y = 1.7697 8.8781e-2x + 6.2301e-4x^2 R^2 = 0.985



y = 1.9238 0.19605x + 1.6226e-2x^2 5.9752e-4x^3 R^2 = 0.999